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TIME MEASUREMENT

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AN INTRODUCTION TO MEANS AND WAYS
OF RECKONING PHYSICAL AND CIVIL TIME

BY

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PREFACE

THIS small book is intended to present in short compass the rudiments of time measurement. No previous knowledge whatever of the subject is presumed. In a book having such an aim it is very undesirable to attempt to cover a great deal of ground, and consequently only so much subject matter has been included as is necessary to illustrate broad features.

The treatment of the subject of weight and spring-driven clocks is mainly historical. It is an error to suppose that the earliest weight-driven clocks of which we have accurate knowledge—those which have come down to us from Plantagenet times either actually or by description—were crude contrivances. The workmanship certainly was rough, but they were anything but crude in conception. It is perfectly possible to use them for illustrating, not of course the refinements, but the broad outlines of modern construction, with the advantage of investing somewhat dry mechanical details with an antiquarian interest. Attention is therefore particularly directed to Chapters V and VIII. It is hoped that the reader who studies these chapters will be left with an enhanced respect for the

attainments of the Middle Ages. Though a good deal has been written about the dial work and the externals generally of these clocks, very little has been written about their movements. Any competent mechanician gifted with the proper antiquarian instinct, who should write a systematic account, with working drawings, of pre-seventeenth century clocks would perform a very worthy task.

Nothing has been more gratifying to the writer than the kindly help which has been given him by all to whom he has applied for information, and he desires to express his sincere thanks to them. Amongst others he must specially mention Sir F. W. Dyson, F.R.S., Astronomer Royal; The Very Rev. J. Armitage Robinson, Dean of Wells; Mr. E. G. Constable, of the National Physical Laboratory; Mr. S. R. Wells, M.P. for the Bedford Division, and Mr. J. J. Hall, of Exeter. Want of space has made it impossible to use all the material supplied by these and other gentlemen, but the writer is none the less grateful to them. It is, of course, understood that none of them are in any way responsible for the statements in the text.

L. B.

BEDFORD, *August* 1923.

NOTE. p. 144. While these pages were going through the press, an innovation was made. Greenwich mean time is now broadcasted daily. L. B.

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CHAPTER I

THE NATURE OF TIME MEASUREMENT

ALTHOUGH everyone is familiar with lapse of time and extension in space, neither time nor space has yet been defined in terms which meet with general acceptance. Philosophers in all ages have speculated on their nature but without coming to agreement. Some, for example, have held that the ideas of space and time are what are called forms of consciousness coming to us by nature independently of experience, the word *form* being used not in the sense of a kind or variety, but in the sense of a background or matrix which serves as a basis for our ideas of other things. Or again, the word is used somewhat in the sense in which we speak of an income tax form or of an army form. A blank cheque is a general form of money draft which can be filled in according to particular needs. Other philosophers again have held the entirely opposite view that the notions of time and space are acquired wholly from particular experiences of occurrences. Space, they say, is an abstraction or generalized notion derived from experiences of the relative positions of concrete

objects. It is the one common general feature which persists after all individual peculiarities of the shapes, sizes, and positions of particular objects have been removed, or as they say, abstracted. Time, also, so it is said, is a similar abstraction derived from experiences of the succession of events.

Fortunately, for purposes of measurement it is not necessary to decide between these conflicting opinions. Interesting and perhaps important as such philosophical inquiries are, they have no immediate bearing either upon ordinary affairs or upon physical science. What is of interest from these points of view is not the nature of time or space in the abstract, but concrete times and spaces. The questions to be answered are such as "How long after a certain event did some other event occur?" or, "How far off is some object from another?" The answers to such questions involve measurement, and to measure anything, whether time or space or anything else, no knowledge of its inner nature is wanted, for measurement consists merely in comparing the thing to be measured with some unit or standard of its own kind. For example, a length is measured by comparing it with a measuring rod which is a material object marked with another length, a comparison which can usually be made by direct application of the standard to the distance to be measured. In this country the standard or unit length is the yard, and to measure an object a yard measure is laid alongside it, if necessary more than once in successive positions end to end, and the length of the object is stated in

fractions or multiples of the unit. The method of direct application of the standard length is not always practicable, but all methods involve it in principle if not actually. As the present subject is time and not length measurement, this matter will not be discussed in further detail, but the facts just stated throw by contrast an important light on the peculiarities of instruments and occurrences used for measuring time and on the assumption upon which this measurement rests.

Time intervals, like lengths, are measured by comparison with a standard. But while length measurement is founded upon direct application of a length standard, no such proceeding is possible with time. The same standard of length can be used over and over again, but a standard of time is a time interval which is a transient thing and once elapsed it can never be recalled. All that can be done is to imitate it by selecting some natural occurrence or by contriving a machine which will go on repeating intervals exactly like it. As a practical consequence of this, it follows that, generally speaking, a complication is introduced into time measuring apparatus which is not needed in measures of length. A yard measure is a very simple thing, but a clock is a complicated machine.

But something further is involved. Direct comparison between successive time intervals being impossible, it is necessary to adopt as time measures either natural occurrences, such as the rotation of the earth, or machines such as clocks, which repeat their movements in cycles with perfect regularity.

The repetition of these cycles marks the time and furnishes its standard. Now the characteristic feature of cycles of movement suitable for time measurement is that all the cycles of a series are performed under similar physical conditions. When the similarity is rigorously exact it is *assumed* that the cycles are performed in equal times; or to look at the matter in another way, equal times may be *defined* as the periods in which such cycles are performed. It is necessary to justify the assumption or the definition, but this can be done by comparing different series of cycles, care being taken that the several series relate to independent phenomena. Take, for example, the cycles of the earth's daily rotation about its axis and of its annual revolution round the sun. There is no discoverable causal relation between them, and yet the number of days which go to a revolution hardly varies at all.[1] The same number of daily cycles always goes to make up the yearly cycle, with a scarcely observable variation. Again, the movements of a clock are independent of those of the earth, and yet a similar concordance is shown. If these movements were not independent there would be no justification for assuming their regularity or for founding a definition of equal times upon them. Concordance between related series of cycles would exist whether or not the cycles were regular, but concordance between independent series would not. It can exist only if

[1] According to Professor Eddington the day is lengthening by about one thousandth part of a second per century, or one minute in 6,000,000 years.—*Nature*, Jan. 6, 1923.

the several cycles of a series are performed in equal times.

It is quite true that no two cycles can in practice be repeated under *exactly* similar physical conditions, but natural occurrences can always be chosen, or clocks made, so that the irregularities are very small. The irregularities can usually be discovered and allowed for. Owing to the independence of the series, irregularities seldom occur at the same time. Clocks, for example, do not all go wrong at once, and it is possible to compare them and adjust such irregularities as arise.

The object of the present book is to give an account of the more prominent natural phenomena suitable for time measuring, and of machines constructed for the purpose. The next two chapters will deal with certain astronomical cycles.

CHAPTER II

THE YEAR

Amongst the many astronomical cycles which might be used for measuring time the most important are those performed by the earth. Not only is man's life regulated by the succession of day and night and by the seasons, but some of these cycles present a constancy and an ease of observation which make them eminently suitable. They have accordingly been adopted by universal consent as the fundamental measures of time. Certain cycles connected with the moon present striking features, but they are more complicated. Their application has been rather to religious observances than to civil and scientific purposes, and their consideration in this book is therefore reserved for the chapter on the Calendar.

No one knows what the absolute movements of the heavenly bodies are, or even whether there is such a thing as absolute movement. The motion of any one body relative to the others can be stated, but as these last may themselves be moving, the absolute motion of the body remains undetermined. There is, in fact, no single object in the universe

known to be fixed, to which the movements of all others can be referred. We have, therefore, to be contented with relative movement, and for this purpose it may be assumed as a method of description either that the earth is fixed while the heavens rotate round it, or that the so-called fixed stars, of which the sun is one, constitute a fixed system within which the earth moves. The former method, or the *geocentric* theory as it is called, is best adapted for the discussion of the periods of time known by the common name of *day*, and the latter, called the *heliocentric* theory, for those called the *year*.

These relative movements of the earth and the celestial bodies give rise, amongst others, to the following five different periods all called years, and to the three called days, which we select on account of their comparative importance :

The Year.

(1) The Sidereal Year.
(2) The Anomalistic Year.
(3) The Tropical Year.
(4) The Common Civil Year.
(5) The Leap Year.

The Day.

(1) The Sidereal Day.
(2) The True or Apparent Solar Day.
(3) The Mean Solar Day.

After a preliminary account of the heliocentric theory the present chapter will discuss the first

three kinds of year. The other two kinds relate more properly to the Calendar.

The Copernican Theory. The introduction of the method of description called the heliocentric theory into modern astronomy is mainly due to Nicolaus Koppernigk, commonly known as Copernicus. He lived about the earlier half of the sixteenth century, and was a native of Thorn in West Prussia, then part of Poland. The theory as it left his hands was very imperfect, for though he broke with tradition so far as to regard the sun as the central body, he still adhered to it in supposing the orbits round the sun to be circular. The circle uniformly described by a moving body was considered by the ancients to be the only perfect form of motion, and since Nature was also perfect, in their belief no other form of planetary motion was admissible. The theory of Copernicus consequently did not give an adequate account of celestial movements until modified by Kepler, who about the end of the sixteenth century discovered that the orbits of the planets were neither circular nor uniformly described.

The heliocentric theory cannot be said to have originated with Copernicus, for it was held by some at all events of the followers of Pythagoras of Samos who lived about 540 B.C., and notably by Aristarchus of Samos (280-264 B.C.). Nevertheless, Copernicus must have the credit of introducing it as a practical method of description, and it has been known by his name ever since his time.

The Earth's Orbit. We now proceed to discuss in some detail the orbit of the earth considered in

relation to the sun and the fixed stars. The fixed stars and the sun, as is well known, do not form an absolutely fixed configuration. Their relative movements in fact are known in many cases to be considerable, but, as their distances apart are very great compared with the orbit of the earth, these movements when perceptible at all are barely so, and may in all instances be ignored for present purposes. In relation to this configuration the earth performs two distinct movements, one of *revolution* [1] round the sun, and another of *rotation* [1] about an axis fixed in it and called the *polar axis*.

The orbits which the planets, the earth as well as the rest, describe round the sun are ellipses, the sun occupying their common focus. The *ellipse* is a curve lying in one plane, and is such that the distances of any point upon it, such as P, Fig. 1, from two fixed points S and H always add up to the same length; that is $SP+PH$ is constant. If SPH be a string attached at its ends to points S and H on a flat piece of paper, and if the string be extended by the point of a pencil at P which is moved about on the paper, the pencil will draw the curve. S and H are called the *foci* and SP and HP the *radii vectores* of P. The curve is an oval as shown, and it can easily be verified by actual measurement with the string that $SP+HP=AA'$, the longest diameter; also that if BB' be the diameter perpendicular to AA' through C, which is midway

[1] The word "revolution" will in future be used consistently as meaning movement of translation of a body round some external centre or axis. "Rotation" will mean spin about an axis within the body.

between A and A', or S and H, then $SB=HB=\frac{1}{2}AA'$. AA' is called the *major axis* and BB' the minor axis. C is the *centre*, and the points A, A', where the curvature is sharpest, are the *apses*. The ratio of SC, or HC, to AC is the *excentricity*. In the case

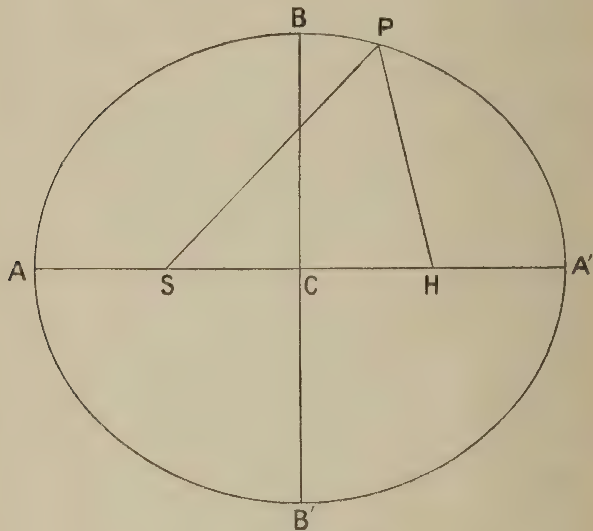


FIG. 1.—THE ELLIPSE.

shown S is midway between C and A and the excentricity is therefore $\frac{1}{2}$. If S and H be moved nearer to C through equal distances along the line AA', the excentricity is, of course, reduced, but in all cases the curve will pass through A and A' provided that the length of the string remains the same. In the limiting case when S and H both coincide with C, the curve becomes a circle with C as centre, but its radius will still be CA. The excentricity is the

quantity which determines the shape of the ellipse whatever may be its size. For if AC be taken of any length and the excentricity be given, S and H can be found at once.

In the case of the earth's orbit the sun occupies one of the foci, say S, but the orbit is very much more nearly a circle than that shown. The actual excentricity is ·0168 instead of $\frac{1}{2}$, and thus S and H are so close to C as hardly to be distinguishable from it on the scale of the figure. AA', the major axis of the orbit, is about 186 million miles, SC is about 1·6 million miles, and consequently SA and SA' are respectively about 91·4 and 94·6 million miles. The excentricity, however, is somewhat variable, but according to an eminent authority it can never exceed ·2.

Since the earth is nearest the sun at the apse A, this point is also called the *perihelion*.[1] Similarly, since SA' is the greatest distance, A' is called the *aphelion*.[1] CA, or CA', which is equal to the arithmetic mean of SA and SA', is called the *mean distance*. The earth's mean distance is thus about 93 million miles.

The Motion of the Earth in its Orbit. The North side of the plane of the earth's orbit is that side on which the terrestrial North Pole lies, and, looked at from that aspect, the earth appears to revolve in a counter-clockwise direction. It moves with an average speed of about 19 miles per second of time, but this speed is not uniform, being appreciably less at aphelion than at perihelion. The rule

[1] περί = near; ἀπό = away from; ἥλιος = sun.

is that equal areas are swept out by the radius vector in equal times. Thus, in Fig. 2, if 1, 2, 3, 4, 5 and 6 (or A), are the successive positions in the orbit at time intervals of one twelfth of a period of revolution starting from aphelion A' and ending with perihelion A, the areas $A'S1$, $1S2 \ldots 5SA$, are all equal. Aphelion, when the motion is slowest,

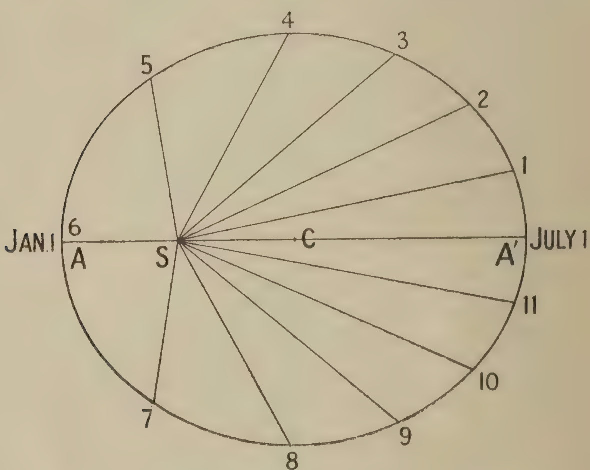


Fig. 2.—Ellipse Divided into Twelve Equal Areas.

is reached about July 1, and perihelion, when the motion is quickest, about January 1, of each year. Thus, the orbital movement of the earth is slower in summer than in winter, though, naturally, the difference is much less than that indicated by Fig. 2 on account of the small excentricity in the actual case.

The Sidereal Year. As the earth revolves, the sun would be seen projected in succession against the

members of the belt of constellations lying on the plane of the orbit were it not for the glare of the sun's light. The sun is, in fact, so seen at times of eclipse. At other times its position amongst the stars is a matter of inference, which, however, presents no great difficulty to astronomers. The sun thus appears to perform a complete circuit of the heavens during a revolution of the earth, and its apparent position in relation to any of the fixed stars can at any time be determined. At the end of one complete revolution of the earth the sun has returned to the same apparent position in relation to the fixed stars. Thus, suppose that the sun, the earth and a star are in a line at a certain time. A revolution is complete when they are again in the same line and in the same relative positions upon it. The time interval of a revolution thus determined is called the *Sidereal Year*, since it refers to the period of revolution in relation to the stars.

The Anomalistic Year. If the earth's orbit were immovable in relation to the fixed stars, the period of time in the orbit from one apse round to the same apse would always be the same. The orbit itself, however, performs a slow revolution in the same direction as the earth's revolution. The motion may be pictured by representing the orbit as a wire upon which a bead representing the earth revolves, and by imagining further the wire to rotate round the solar focus while the bead moves upon the wire in the same direction. The motion of the apse is very slow, since it takes about 110,000 years to complete a circuit of the heavens. But if

the year be reckoned as the time from perihelion to perihelion, or from aphelion to aphelion, it proves, in consequence of the apsidal motion, to be about 4½ minutes longer than the sidereal year. For, starting say from perihelion and completing a sidereal year, the perihelion will no longer be found where it was before, but will have moved onwards through a distance which takes the earth about that time to traverse. The year thus reckoned is called the *Anomalistic Year*.[1] It is not of equal practical account with the other two kinds of year.

The Equinoxes and the Tropical Year. The sidereal and the anomalistic years have no relation to the earth's axial rotation, and they are much inferior in importance to the Tropical Year, which is the subject of the present section. The importance of the Tropical Year lies in the fact that it agrees with the Seasons, and it differs from the two just discussed in that the points on the orbit which determine it are themselves determined by phenomena arising out of the rotation.

The fact of the earth's rotation furnishes those important landmarks, the North and South terrestrial poles, at each end of the diameter about which the rotation takes place, and it consequently determines the terrestrial equator which encircles the earth midway between the poles. Were there no rotation there would be no poles, at least as we

[1] Possibly because of some connexion with the angles called "anomalies" in astronomy, but why these are so called the writer does not know.

understand the term. The plane of the equator is inclined at an angle of about $23\frac{1}{2}$ degrees to that of the earth's orbit, and this inclination is subject only to fluctuations which are so slight as to be negligible for present purposes. But though this angle is substantially constant, the direction of the plane of the equator in space—relative to the fixed stars, that is to say—is not constant. The axis is subject to a slow gyrating or wobbling motion like that of a top, and for reasons which are precisely the same in principle as those which influence a top. These reasons need not detain us, our present concern being with the fact. The motion may be more accurately described by stating that the earth's polar axis describes a cone whose axis is a line through the earth's centre, perpendicular to the plane of the orbit. The inclination of these axes to one another is also $23\frac{1}{2}$ degrees, and the equator naturally partakes of the gyrating motion. The motion is very slow, one gyration taking 25,000 years to complete. It should be remarked that these gyrations take place in a direction opposite to that of the rotation of the earth, for while the earth rotates in the same direction as that in which it revolves, namely counter-clockwise looking from the North, the revolutions of the North terrestrial pole due to the gyrations of the polar axis take place clockwise.

We shall now consider the various aspects which the sun presents to the earth in the course of an orbital revolution, due solely to the mutual inclination of the planes of the orbit and the

equator, neglecting for the moment changes in the direction of the axis, after which these changes will be taken into account and it will be shown how the period called the Tropical Year arises from them.

In Fig. 3 the earth's orbit and the equator both viewed edgeways are represented so as to appear as mere lines to the spectator, the former by the horizontal line, and the latter in three different positions by the sloping line QQ' which makes an angle of $23\frac{1}{2}°$

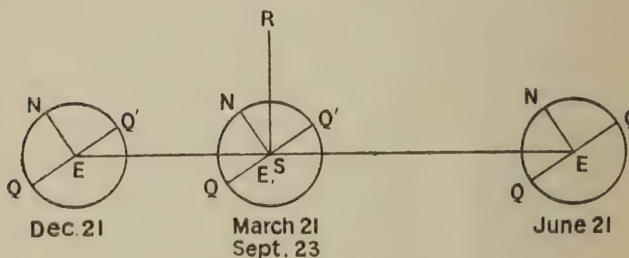


Fig. 3.—Earth and Orbit seen Edgeways.

with the horizontal line. NE represents the polar axis, N being the North pole. The circles represent the earth, and S is the sun. The earth, while actually revolving in its own orbit, appears in the present aspect to a spectator to oscillate to and fro between two extreme positions. While performing these oscillations it will occupy two intermediate positions, one in going and the other in returning, where S, the sun, will pass through the plane of the equator from North to South or from South to North, and will therefore seem for an instant to be on the plane of the equator. The middle circle in Fig. 3

corresponds to one of these positions.[1] As will be seen in the next chapter, day and night are then equal all over the world, from which fact these positions are called the equinoxes. The Vernal equinox, when the sun crosses the equator from south to north, marks the commencement of Spring in the northern hemisphere of the earth, and occurs about March 21. The Autumnal equinox, when the sun returns to the south side of the equator, occurs about September 23 and marks the commencement of Autumn. Both these events correspond to the middle circle of Fig. 3.

The extreme positions of the circles in Fig. 3 correspond to the *solstices*, where the sun, as it were, pauses in its northerly or southerly movement and

[1] The reader who is coming to this subject for the first time cannot expect to understand the text without some difficulty unless he is unusually gifted with visualizing powers. If, however, he makes use of an orrery he will reduce the difficulty very considerably. Orreries are models which imitate planetary movements. They are usually expensive, and if the reader has not access to one he can improvize a primitive but quite effective form out of an apple, a knitting needle or skewer, and a small round table. Stick the skewer through the apple from stem to calyx. The skewer represents the polar axis, the calyx the North Pole and the stem the South. A cut midway round the apple represents the terrestrial equator. The edge of the table represents the earth's orbit, and the table top the plane of the orbit. The sun is supposed to be at the centre of the table. Hold the apple close to the edge so that its centre is opposite the edge, and tilt the skewer to represent the obliquity of the equator. Now move the apple round the edge, keeping the skewer parallel to itself all the time. All the effects stated in the text may then be observed. Further realistic effect may be given by placing a nightlight or short candle in the middle of the table to represent the sun. Excepting for the opacity of the table which partly obscures the light, the illumination of the apple will imitate day and night.

commences to return towards the equator.[1] The *Summer Solstice*, when the sun is furthest north, occurs about June 21 and the *Winter Solstice* about Dec. 21, when it is furthest south. These points or instants, it may be observed, do not correspond with perihelion and aphelion, as a comparison with the dates already given will show. The horizontal line in Fig. 3 is therefore not the major axis of the earth's orbit, though at the present period of the world's history it is not far off.

The effect on the positions of the equinoxes of the wobbling or gyrating motion of the earth's axis will now be taken into account. It is clear from what has been said above that these positions depend upon the direction of the polar axis relative to the fixed stars. If this direction remained unchanged [2] there would be no change in the positions of the equinoxes, and a year, reckoned by a circuit of the orbit from one equinox round to the same equinox, would be the same as a sidereal year. But if the axis gyrates the equinoxes shift round on the orbit in the same direction as the gyration and at the same rate.[3] Since the gyrations are clockwise, the

[1] Hence the word "Tropic" from τρέπω (=I turn). No doubt the Tropical Year is so called from its intimate connexion with the seasons, and hence with these "turning" points.

[2] Or even if the axis merely rocked, the rocking being always directed towards the same quarter of the heavens.

[3] It is in the writer's opinion impossible to explain this adequately without a model. The reader can verify the statements in the text with the help of the apple model described in a previous footnote, by noticing the effect of rocking and wobbling the skewer slowly. He can also try the effect of rocking and wobbling a penny inside a ring formed by the thumb and forefinger of one hand. The ring represents the plane of the

movement of the equinoxes is also clockwise, or contrary to the direction of revolution in the orbit. The movement is very slow, as it takes 25,000 years to complete a gyration with reference to the stars. This corresponds to a movement of the equinoxes along the orbit of about 50 seconds of arc a year. The result, however, is that the equinoxes advance slowly to meet the earth as it revolves, so that the period of a revolution counted with reference to the equinoxes is rather shorter than the period of a revolution counted with reference to the fixed stars. The latter period, as has been seen, is the Sidereal Year, and the former is called the *Tropical Year*. The difference in time between the two is about 20 minutes, this being the time in which the earth describes 50 seconds of arc of its orbit.

The movement of the equinoxes along the orbit is called the *Precession of the Equinoxes*. It was well-known to the early astronomers and its rate was determined by Hipparchus of Rhodes, the most

earth's orbit and the penny that of the equator. A still better plan is to cut a circular disk out of the middle of a piece of cardboard; mount the disk on a pencil passed skewwise through its centre after the manner of what mechanicians call a "drunken" wheel or cam; then, by means of the pencil held at right angles to the card, twist the disk round inside the hole in the card left by the removal of the disk, after having cut away the edges a little to give clearance; the points where the disk and the card cross will then, of course, move round in the direction of twirling, and this is exactly the movement of the equinoxes. The pencil is in the direction *ER*, Fig. 3.

It is hoped that with these hints the reader will be able to construct other simple illustrative models. Something of the kind is indispensable, for though the movements are quite easy to grasp when seen in a model, very few beginners can understand them without one. The writer certainly could not.

famous of them, who lived about 150 B.C. One of the factors which determine its amount is the rate of rotation of the earth, and thus the rotation doubly controls the Tropical Year, for firstly, the existence of the rotation provides the North and South poles and these determine the positions of the equinoxes, and secondly, the rapidity of the rotation determines their rate of movement.

The Relative Movement of the Apses and the Equinoxes. It has been seen that the apses move forwards on the orbit about $\frac{1}{110,000}$ of a revolution per year, in the same direction as the earth revolves in it, while the equinoxes recede about $\frac{1}{25,000}$ of a revolution. The apses and the equinoxes thus meet and pass one another, moving relatively at the rate of $\frac{1}{110,000}+\frac{1}{25,000}$, or about $\frac{1}{21,000}$ of a revolution per year.[1] The same configurations of equinoxes and apses are therefore repeated after intervals of 21,000 years, though these configurations are not necessarily similarly disposed in relation to the fixed stars. The line of equinoxes thus coincides with the line of apses, that is, with the major axis of the ellipse once every 10,500 years.

[1] A model will show this. Cut out an ellipse in cardboard, tracing it by the string method above described; rule the apsidal line on it, and pin it down on a board by a pin through one focus. Then cut out a strip of cardboard and pin it down by the same pin. Rotate the ellipse counter-clockwise, and the strip which represents the line of equinoxes clockwise but faster, and observe the crossings of the strip and the apsidal line.

CHAPTER III

THE DAY

If novelists are to be believed, one of the elegant accomplishments taught in academies for young gentlewomen a century or so ago, and perhaps later, was what was called "The Use of the Globes." It is to be regretted that this subject has not been retained and extended to other schools as well, for the present chapter, which relates to nothing else, need not then have been written. But things being as they are, it is necessary to deal with the matter. A discussion of time would obviously be incomplete if one of its main divisions, the day, were left undefined, and for this purpose the facts which determine the day must be explained. It is not to be denied that this explanation presents some difficulties unless approached in the proper way. If the wrong way is chosen, which is to rely upon paper diagrams, the difficulties, as the present writer knows to his cost, are serious. They arise from the necessity of keeping before the mind's eye, lines, circles, and other marks within and upon a sphere, many of which must be imagined to be in motion, and very few persons possess the power of doing

this adequately. But when seen in a model the matter is simple enough, and it will therefore be supposed in what follows that the reader has constantly before him one or other of the models to which reference is made.

The Celestial Sphere. The heavenly bodies appear to a spectator on earth as though projected on to the surface of a sphere of great but undefined size, at the centre of which he is situated, and which appears to rotate from East to West about the earth's polar axis. This sphere, which was supposed in early times to exist physically, is called the *celestial sphere*, or the *celestial concave.* It is divided into equal parts, one visible and the other invisible, by the plane of the spectator's horizon, which, though actually the plane touching the earth at the point where he stands, may for present purposes be taken as passing through the earth's centre on account of the insignificant size of the earth compared with celestial distances. The inclination of the polar axis to the plane of the horizon is the same as the observer's terrestrial latitude, and the great circle,[1] in which this plane, supposed produced, cuts the celestial sphere, is the observer's celestial horizon, or briefly, his *horizon.* The plane of the earth's equator cuts the celestial sphere in the *celestial equator*, which is another great circle, and the plane of the earth's orbit in yet another called the *ecliptic*.

[1] A great circle of a sphere is its section by any plane passing through the centre. All other circles on the sphere are called small circles.

The Celestial Globe and the Armillary Sphere. It is very improbable that the reader will be able to follow the remaindeı of this description, if, indeed, he has succeeded in following it so far, without reference to a model. He should, therefore, make use of a celestial globe, if available. A celestial globe is a model of the celestial sphere, upon which the main stars are shown, as objects are shown on a terrestrial globe. The circles above described are plainly marked on the globe except the horizon, which is represented in good globes by the ring-shaped top of the stand on which the globe is mounted. As, however, celestial globes of adequate quality and size are very expensive, we proceed to describe an apparatus which can be used instead, and which can be made at a cost of about half-a-crown by almost anyone with the exercise of reasonable care, no very great accuracy being needed. Such further definitions as are required will be given in the course of the description. If, however, a good celestial globe is available, the reader should have no difficulty in adapting the subject matter to it for himself, without troubling to make the model.[1]

The apparatus is a form of armillary sphere, which is a skeleton celestial globe made up of metal strips or wires. The armillary sphere is said to have been invented, or at all events improved, by Eratosthenes, an Alexandrian astronomer, who lived about 300 B.C. It was much used as an observing

[1] For directions for making the model *see* Appendix. Some details shown in the Figures, but not mentioned in the text, are referred to in the Appendix.

instrument by the early astronomers. Referring to Fig. 4, *A* is a circular board representing the plane of the horizon of the observer, who is supposed to

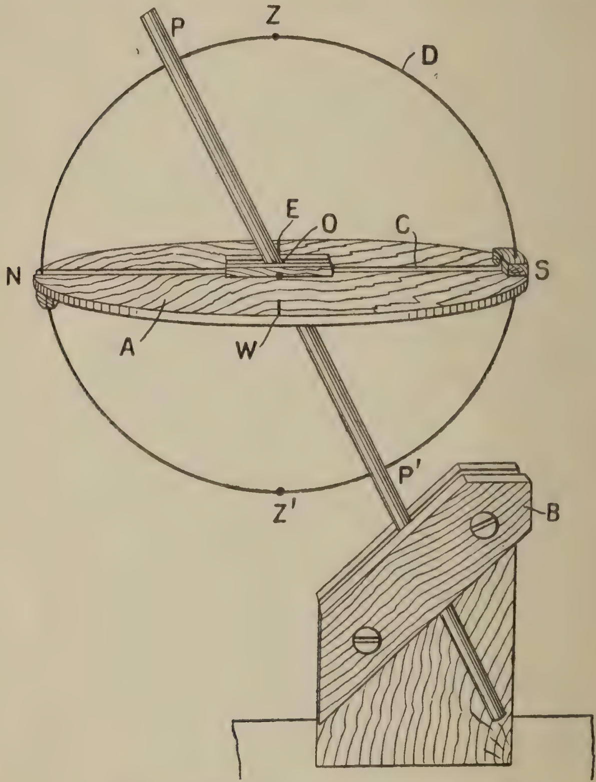


Fig. 4.—Armillary Sphere: Interior Parts.

be stationed at its middle point *O*. The edge of the board represents the celestial horizon. The board is pivoted at *O* to a rod *PP′* by a pin in its plane at right angles to the rod, which represents

the polar axis and is adjustably fixed in a clamp *B*. The pivot enables the rod and board to be set at any angle to one another corresponding to the observer's latitude. For example, for an observer at the North Pole, in latitude 90° that is to say, they are set at right angles. For an observer in London the angle *PON* would be about $51\frac{1}{2}°$, which is the latitude of London. For an observer on the equator, in latitude zero, the board is folded up against the rod. To enable the board to assume this last position it has to be slotted diametrally as shown at *C*, but it need not be made to fold up against the rod in more than one way. A circular wire *D* passes through the rod and through the board as near as possible to its edge at the ends of the slot. It will be noticed that when the wire is so positioned it passes through two important points, *Z* and *Z'*, which are called respectively the *zenith* and the *nadir*, and lie on the celestial sphere immediately over the observer's head and beneath his feet. The wire represents the observer's celestial meridian or, shortly, his *meridian*. The meridian may be defined as the great circle in which the celestial sphere is cut by a plane passing through the polar axis and the observer's zenith (or nadir), and it is his most important landmark for observing celestial objects. When, in the course of the rotation of the celestial sphere, an object is observed to cross the meridian, the event is called a *transit*. The meridian is actually a great circle of the celestial sphere, though, of course, as it is fixed with reference to the observer it does not move with it. In the model as assembled

the wire lies a little inside the celestial sphere, but it must be imagined to lie on it. The points N and S, where the meridian crosses the horizon, are called the *North* and *South points* (not poles). A line in the prolongation of the pivot, at right angles to NS, cuts the horizon in the *East* and *West points*, E and W. In an observatory the meridian is represented by a short vertical mark inside a telescope. The mark is visible to an observer looking through the telescope, which is rotatably mounted on an axis pointing East and West so that it can be elevated to bring the mark into coincidence with any desired part of the meridian. The transit of a celestial object occurs when it crosses the mark. A telescope mounted in this way is called a *transit instrument*, and more will be said about it in a future chapter.[1]

The foregoing parts of the apparatus, excepting the polar axis, relate to the observer's position on the earth, and change their position if he changes his. We now come to the celestial sphere, which is independent of him. The celestial sphere is represented by a wire cage shown in Figs. 5 and 6, which are views at right angles to one another. The cage is built up of twelve semi-circular pieces of wire inserted at their ends into small disks G, H, of hard wood, and are spaced apart equally so as to form six complete great circles. The centres of the disks are at the

[1] In celestial globes the meridian is represented by a brass circle, within which the globe is pivoted. The circle is rotatably mounted in the stand, the horizon ring being notched to receive it. The globe can thus be adjusted for any latitude.

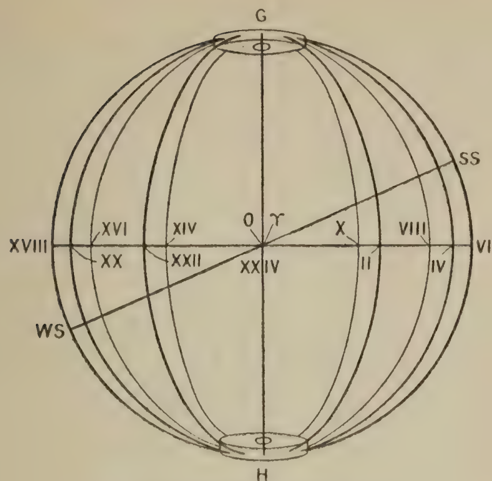


Fig. 5.—Armillary Sphere: Cage.

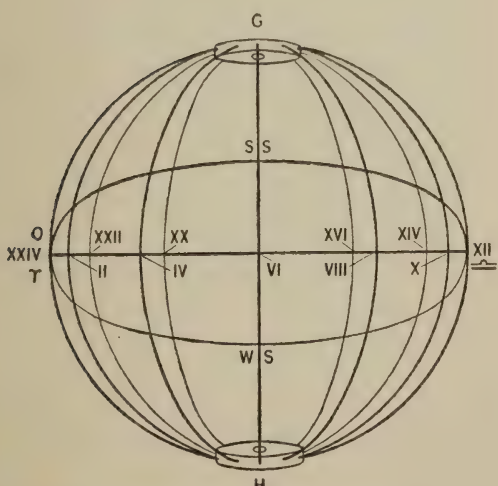


Fig. 6.—Armillary Sphere: Cage.

North and South celestial poles, and central holes are bored in them to receive the wooden rod when the apparatus is finally assembled. Midway between the poles a wire, marked with Roman numerals in the Figures, encircles the wire ribs and represents the celestial equator. The oblique circular wire, *SS-WS*, represents the ecliptic. It makes an angle of $23\frac{1}{2}°$ with the equatorial wire and intersects it at the points XXIV and XII. These points are the projections on the celestial sphere of the vernal and autumnal equinoctial points explained in the last chapter. The point corresponding to the vernal equinox is called the *first point of Aries,* because when first noticed many centuries ago, it was situated in the constellation Aries. On account of the precession of the equinoxes it has since moved backwards by about 30° into the constellation Pisces, but the ancient name is still preserved, and it is indicated by the symbol ♈, by which the zodiacal sign Aries is conventionally represented, a symbol obviously intended to suggest the horns of a ram. The point corresponding to the autumnal equinox for a similar reason is indicated by the symbol ♎, which represents conventionally Libra or the scales, though the point is now in the constellation Virgo.

The complete model is shown in Fig. 7. When assembled, the parts shown in Fig. 4 are inside the cage, and are so situated that the centre *O* of the disk where the observer is supposed to be, is at the centre of the cage, which is kept in position on the rod by small pins. The disk is made with a little clearance between it and the cage so as to allow the latter to

be rotated freely on the polar axis. A quarter of an inch clearance should be enough. It should be

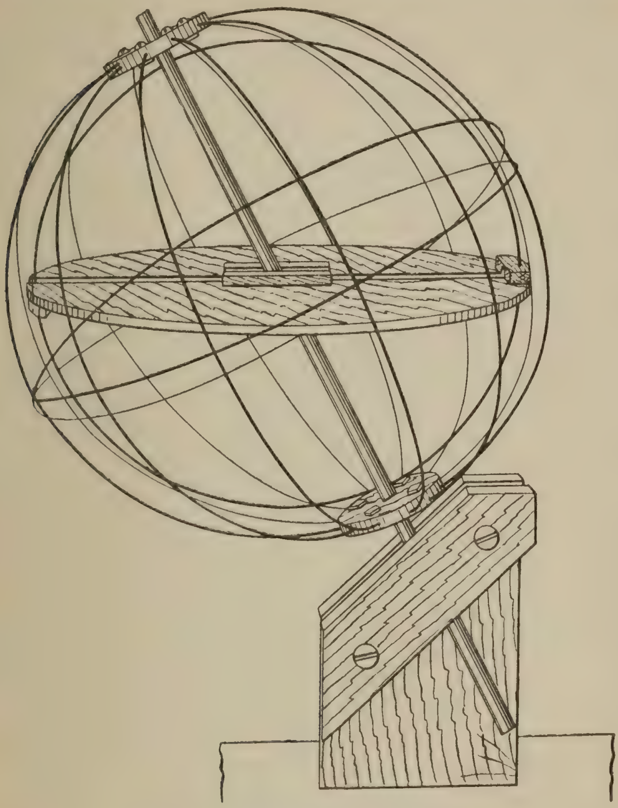


FIG. 7.—ARMILLARY SPHERE COMPLETE.

noticed that however the disk *A* be tilted with reference to the polar axis, that is to say for whatever latitude the apparatus be adjusted, the equator always cuts the horizon in the East and West points,

excepting in the particular case when it is adjusted for latitude 90° (corresponding to the North or South poles). The equator and the horizon then coincide.

In order to demonstrate celestial movements, adjust the horizon disk on the polar axis so that the angle between them is equal to the spectator's latitude. Then clamp the polar axis so that the disk is horizontal, attach a clip in any position to one of the wires of the cage to represent a celestial object, and rotate the cage from East to West, that is clockwise if the spectator is in the Northern terrestrial hemisphere. A star or other object *rises* when it comes above the horizon and *sets* when it goes below it. The reader should notice the effects of changing the latitude of the observer and the position of the clip. He should observe, for example, that for every latitude, excepting the actual poles, all bodies on the equator are as long above the horizon as below it when the sphere is rotated uniformly. Also, that there are certain regions round each pole of size depending on the spectator's latitude, the stars within one of which do not set, and within the other do not rise, and he should determine by measurement or inspection the relation of the diameters of these regions to the latitude. All measurements should be made with a tape or piece of paper along the arc of a great circle and not with a straight rule direct from point to point. It should also be noted that all objects *on the same semi-circular rib* cross the meridian at the same time, or in other words their transits occur at the same instant.

The Sidereal Day. The time interval between two successive transits of the first point of Aries is called the *Sidereal Day.* This interval is not absolutely the same as the period of a rotation of the earth in relation to the fixed stars, which is the interval between two successive transits of any one of them. As was seen in the last chapter, the equinoxes have a slow retrograde motion amongst the stars, and this makes the transit interval of the first point of Aries about one-hundredth of a second of time longer than that of any one of the fixed stars. For practical purposes this difference is slight, and such as it is, it can easily be allowed for. In fact, since there is no celestial object situated at the first point of Aries by which it can be observed directly, its position and therefore its time of transit have to be computed from the positions and transits of selected fixed stars.

The sidereal day is divided into 24 equal hours, commencing from the transit of the first point of Aries, which is *sidereal noon.* The hours are again divided into minutes and seconds in the usual way. Each sidereal hour therefore corresponds to one twenty-fourth of a rotation of the celestial sphere, and since one rotation corresponds to 360 degrees of arc, a sidereal hour corresponds to 15 degrees. The sidereal year contains very nearly $366\frac{1}{4}$ sidereal days.

Hour Circles and Angles. The *Hour Circle* of any celestial object is the half great-circle passing through the object and terminated by the celestial poles. The ribs of the cage, for instance, are some

of these hour circles, and correspond to 2, 4, 6, etc. hours after sidereal noon. Some of them are marked accordingly in the Figure in Roman numerals. The pairs of hour circles zero (or XXIV) and XII, II and XIV, etc., make up complete great circles.

The *Hour Angle* of any object is the angle through which the celestial sphere has yet to rotate before the next transit of the object. Another way of defining the hour angle, which, however, amounts to the same thing, is to say that it is the angle reckoned eastwards between the meridian and the hour circle of the object. Hour circles are reckoned in sidereal time at the rate of one hour to 15° of arc measured along the equator.

Right Ascension and Declination. Objects are located on the celestial sphere by *Right Ascension* and *Declination.* These correspond exactly to terrestrial longitude and latitude. Right Ascension is measured along the celestial equator towards the east, the zero being the first point of Aries, just as the zero of terrestrial longitude is the meridian of Greenwich. It is usually reckoned in hours, minutes, and seconds of sidereal time instead of degrees, minutes, and seconds of arc. Reckoned by time, the Right Ascension of any object is, therefore, the time which elapses between the transit of the first point of Aries and that of the object. Unlike longitude, it is reckoned all the way round the equator eastwards from zero back to zero (or XXIV hours), while longitude is reckoned from zero to 180° east *or* west. Declination is

precisely the same as terrestrial latitude. It is reckoned north or south of the equator and is expressed in degrees, etc.[1]

The continual shift backwards of the first point of Aries causes a yearly increase of about 50 seconds of arc in the Right Ascensions of all the fixed stars. A similar effect would be produced on terrestrial longitudes if Greenwich were to shift progressively along the east and west line at the rate of about 1050 yards a year. The precession of the equinoxes has no effect on declinations.

The Motion of the Sun in the Ecliptic. The counterpart, as seen from the earth of the earth's revolution in its orbit from East to West, is the yearly motion of the sun in the ecliptic from West to East, which is the opposite direction to the rotation of the celestial sphere. At the point ♈, Figs. 5 and 6, the sun crosses the equator from South to North, and thence moves eastwards along the ecliptic at the average rate of about 1° of arc per day, that is, by about twice its own diameter. On a model of a foot in diameter this distance corresponds to about one-tenth of an inch. As the sun moves onwards in Right Ascension its North Declination increases up to the summer solstice, *SS*, corresponding to the position of the right hand circle in Fig. 3. The solstice occurs on June 21, and the sun's North Declination is then at its maximum and equal to the

[1] Celestial latitude and longitude are also used, but the zero circle of celestial latitude is the ecliptic and not the equator. The zero point is the first point of Aries as before. Another system of celestial location is "Galactic co-ordinates," in which the zero circle is the Galaxy or Milky Way.

obliquity of the ecliptic, or $23\frac{1}{2}°$. Its Right Ascension is 6 hours. Aphelion, July 1, occurs about an inch on the model from the solstice. The North Declination decreases to zero at the autumnal equinox ♎, reached about September 22 or 23, where the sun crosses the equator to the south. The winter solstice *WS*, corresponding to the left hand circle in Fig. 3, is reached about December 21. The South Declination is then at its maximum. Perihelion, reached January 1, is about an inch further on, on the model. After the winter solstice the sun's South Declination decreases to zero at the vernal equinox, reached again on March 21.

The sun's motion in the ecliptic is not uniform, on account of the excentricity of the orbit and the variable speed of the earth in it, the half circuit from ♈ to ♎ taking about 5 days longer than the other half. The motion is slowest at aphelion and fastest at perihelion. The reader should follow these movements with the aid of a celestial globe or the armillary sphere, placing a clip on the ecliptic, if the latter instrument is used, to represent the sun, and rotating the globe or the cage in order to note the difference in the length of the day [1] compared with the night, and the compass bearings of the points of rising and setting.

In the latitude of London, about 51° 30′ N., the sun rises at the summer solstice approximately 40° North of East measured along the horizon, and

[1] The word "day" is here used as opposed to "night," meaning the period during which the sun is above the horizon. Hitherto the word has meant the interval between two successive transits of the same celestial object.

the same amount South of East at the winter solstice. Or at least these *would* be the points of rising were it not for atmospheric refraction, which causes the sun to appear rather earlier and a little further towards the North on both occasions. Similarly, refraction delays the apparent setting.

The True Solar Day. The *true solar day* is the interval between two successive transits of the sun, and *true solar noon* is the instant of transit of the sun's centre. Reference to the model will show, if it is not already obvious, that owing to the eastward movement of the sun in the heavens, this interval is longer than the sidereal day. It is, in fact, about 4 minutes longer on an average. The length of the true solar day, however, is variable, as will be shown in the next section, on account of the obliquity of the ecliptic to the equator and the variable movement of the sun in the ecliptic.

The number of true solar days in the tropical year is one less than the number of sidereal days, since the sun revolves relatively to the celestial sphere once in the course of the year in the opposite direction to the daily rotation.

True solar time is the time kept by the sun-dial, as will be explained in the next chapter.

The Mean Solar Day. The Equation of Time. The *mean solar day* is the length of the true solar days averaged over a tropical year. If an imaginary body—the *mean sun* as it is called—were to perform the circuit of the *equator* with uniform motion while the true sun performs the circuit of the ecliptic, the interval between successive transits of the mean sun

would be the mean solar day, and *mean noon* would be the instant of transit. Greenwich mean noon is the instant of transit of the mean sun across the meridian of Greenwich, and *Greenwich mean time* is the time kept by a clock which indicates twelve o'clock at Greenwich mean noon. The mean solar day is divided into 24 equal hours, and these into minutes and seconds, which divisions, of course, differ in length from the corresponding divisions of the sidereal day.

The difference in time between true noon and mean noon is called the *equation of time*.[1] It is reckoned positive if it has to be added to true time in order to obtain mean time, that is, if the sun-dial is slow upon a mean time clock, and negative in the reverse case. Almost the whole of it is accounted for by (1) the obliquity of the ecliptic, and (2) the excentricity of the earth's orbit.[2] The effects of these will be considered separately and then added together.

Neglecting for the moment the excentricity, we get a condition which would exist were the orbit circular and uniformly described. The sun, accordingly, would move uniformly in the ecliptic. We shall denote a sun moving in this way along the ecliptic by $S(E)$ and the mean sun which moves in the equator by $S(M)$. The differences between the times

[1] The word *equation* is, of course, not used in the sense in which it is used in algebra.

[2] Other causes, such as a slight irregularity in the precessional motion of the equinoxes due to what is known as "nutation" are here left out of account. For a full discussion of the equation of time reference must be made to works on Astronomy.

of transit of $S(M)$ and $S(E)$ can readily be demonstrated on the armillary sphere or on a celestial globe, by marking off equal distances of say three inches each along the ecliptic and equator, starting from the first point of Aries. These distances on a sphere of twelve inches diameter will be described by $S(E)$ and $S(M)$ in equal time intervals of about a month, and their extremities will be corresponding positions of $S(E)$ and $S(M)$. On rotating the sphere, it will be found that $S(E)$ and $S(M)$ cross the observer's meridian at the same time at the equinoxes and the solstices. Between each equinox and the next solstice $S(E)$ crosses the observer's meridian before $S(M)$, the maximum difference, which is about 10 minutes, occurring approximately half-way. The sun-dial is therefore in front of the clock and the part of the equation of time due to the obliquity of the ecliptic is negative. Similarly, between each solstice and the next equinox the equation of time is positive, with a maximum about half-way. The equation of time arising from this cause is shown by the curve A, Fig. 8. The vertical lines are spaced months being indicated by their initial letters. apart at intervals of a month each, the names of the The lengths between the zero line and the curve A of the vertical lines are proportional to this part of the equation of time.

To take into account the part of the equation of time arising from the excentricity of the orbit we suppose the true sun S and the imaginary sun $S(E)$ to start from perihelion together, and move along the ecliptic. S will immediately gain upon $S(E)$,

which is moving uniformly. It will continue to gain until about half-way towards aphelion when it will begin to lose, and $S(E)$ will catch it up and pass it at aphelion. The relative movements of S and $S(E)$ will be reversed from aphelion to perihelion when the two will be together again, and so on. The curve B, Fig. 8, represents this

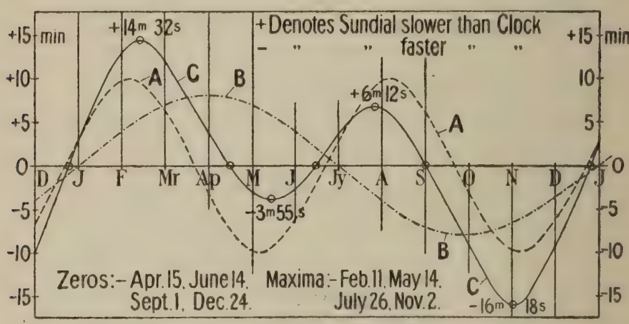


FIG. 8.—EQUATION OF TIME CURVES.

part of the equation of time, the maximum value of which, positive or negative, amounts to about 8 minutes.

The combined effect of both causes is found by adding the vertical distances of the curves from the zero line if these lie on the same side of the line, and subtracting them if on opposite sides. The result is the curve C, which shows that the equation of time vanishes four times a year. Its greatest values, positive or negative, are indicated in the figure.

Sunrise and Sunset. The times of sunrise and sunset are determined by the position in the heavens

of the true sun, while noon is determined by the position of the mean sun. It follows, therefore, that noon divides the day (*i.e.* the period of daylight) into equal portions only at those times when the equation of time vanishes. This accounts for the phenomenon which often attracts notice during the second half of December that the afternoons do not shorten appreciably between about December 14 and December 21, although the days are getting shorter, while from December 21 to January 1 the sun appears to rise progressively later, though the days are lengthening.

Local Time. Since places having the same longitude are on the same meridian, mean noon must occur at the same instant for them all. But as the earth rotates at the rate of 15° of longitude per hour the mean noons of places in different longitudes will differ accordingly. Thus, all places differing in longitude have their own local time, and to avoid the inconvenience of different time reckonings in possibly neighbouring places it is agreed to keep the same time over large areas. Greenwich mean time, for instance, is kept all over the United Kingdom. In very large countries like the United States, the country is divided into districts, over each of which the same time is kept. The custom of keeping local time, is, however still preserved in certain places, or was until recently. Until the introduction of Summer and Winter time the city of Canterbury, for instance, observed for purely local purposes a time which was three minutes in front of Greenwich.

The following figures may be of interest : [1]

The Sidereal Day	=23 hrs. 56 mins. 4·090 secs. of mean solar time.
The Mean Solar Day	=24 hrs. 3 mins. 56·556 secs. of sidereal time.
Tropical Year	=365 days 5 hrs. 48 mins. 45·98 secs.
Sidereal Year	=365 days 6 hrs. 9 mins. 8·97 secs.
Anomalistic Year	=365 days 6 hrs. 13 mins. 48·09 secs.

The lengths of the years are in mean solar time. The figures refer to the year 1900, but the differences in this respect between one year and another are almost infinitesimal.

[1] Young's *General Astronomy*, 1904 edition.

CHAPTER IV

TIME-PIECES

The natural cycles described in the preceding chapters have forced themselves upon mankind as main time standards on account of their intimate bearing on human affairs. But there are obvious drawbacks to their exclusive use. It is not always convenient or even possible to observe the heavenly bodies, though as a matter of fact, out-of-door labourers often depend upon nothing else and make surprisingly accurate guesses at the time from the sun's position. But determinations such as these are not nearly refined enough for general use, and observations, when exact, relate to intervals such as the day and year, which are for ordinary purposes too long. Resort has, therefore, to be made to artificial cycles which subdivide the day into equal intervals, and the most familiar machines for producing such cycles are weight or spring-driven clocks. These, which will be described in succeeding chapters, are, however, a comparatively recent invention, and before they came into use other contrivances were employed, of which the remainder of the present chapter will give a short account.

Water Clocks. It is quite unknown who first observed the regular flow of water through a small hole and turned it to account for measuring time. It is certain, however, that *Clepsydrae*, as apparatus made on this principle are called, were in use in all parts of the civilized world in ancient times. They were found in Britain by Julius Caesar. The applications of the principle varied considerably. In the simplest forms the drip from a hole in the bottom of a bowl was collected and measured, or the level in the bowl was noted. An ornate British specimen of date about 50 A.D. is in the Cambridge Archaeological Museum.[1] An Egyptian specimen, a cast of which is in the South Kensington Museum, dates from the reign of Amenhotep III., who was a predecessor of the now famous Tut Ankh Amen. He reigned from 1415 to 1380 B.C., a century or more before the time of Moses. It shows the varying hour graduations required by the peculiar time reckoning of ancient nations explained further on. In a modified form of this kind of apparatus the empty bowl was set floating in water and the time it took to sink noted. In more elaborate contrivances the drip was received in a vessel containing a float which rose with the level of the water and actuated a hand or other indicator. Since the rate of drip from a vessel depends upon the depth of liquid in it, it was necessary to furnish means for keeping the container full. Clepsydrae are said to have been introduced into Rome by P. Cornelius Scipio Nasica,

[1] See *Proceedings of the Society of Antiquaries* (London), xxvii. p. 88.

157 B.C., and were used to restrain the verbosity of orators. They were known to the Greeks at a much earlier date. Athenaeus, a Greek writer who lived in Egypt and at Rome about 250 A.D., states in his

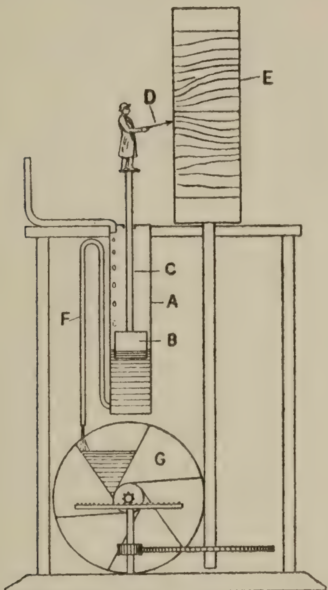


FIG. 9.—WATER CLOCK OF KTESIBIUS.

Deipnosophistae[1] that Plato (*circa* 370 B.C.) made one which played on pipes during the night when the index could not be seen.

Vitruvius, a Latin writer on architecture who lived in the times of Julius and Augustus Caesar, ascribes the invention to Ktesibius of Alexandria about 245 B.C., but it is probable that Ktesibius

[1] *Banquet of the Learned.*

was only the first to apply wheel-work, which was already well known but otherwise applied long before his time. Fig. 9 shows the principle of the water clock of Ktesibius. It is interesting not only as being probably the first time-piece to which wheel-work was applied, but as showing one of the devices by which the Greeks got over the difficulty arising from the unequal lengths of their hours at different seasons. The Greeks, amongst other ancient nations, reckoned their day from sunrise to sunset, dividing it into twelve equal hours, the length of which therefore varied with the time of year. Water drips gradually and uniformly into a vertical tube *A* containing a float *B* on the end of a rod *C* which carries a pointer *D*. The pointer indicates the time on a scale on a vertical cylinder *E*. When the tube *A* is full, which occurs every 24 hours, it is discharged by a siphon *F* on to a water-wheel *G*, the pointer then falling to its lowest position and commencing again to rise as the tube *A* fills. The water-wheel has six buckets and is thus rotated one sixth of a revolution every 24 hours. It is connected by toothed gearing as shown to the cylinder *E* in such a way as to cause the latter to rotate once in 366 days—or once a year, approximately. The cylinder thus presents a fresh aspect to the time pointer every day, and carries scales graduated for the time of year. The overall length of each scale is, of course, the same, since the pointer moves through the same distance every 24 hours. But the scales differ in having the hour divisions corresponding to daylight or night time crowded

together or spread apart according to the time of year. Fig. 10 shows a chart which, if wrapped round the cylinder so that the vertical edges meet, would, when presented by the mechanism in its proper

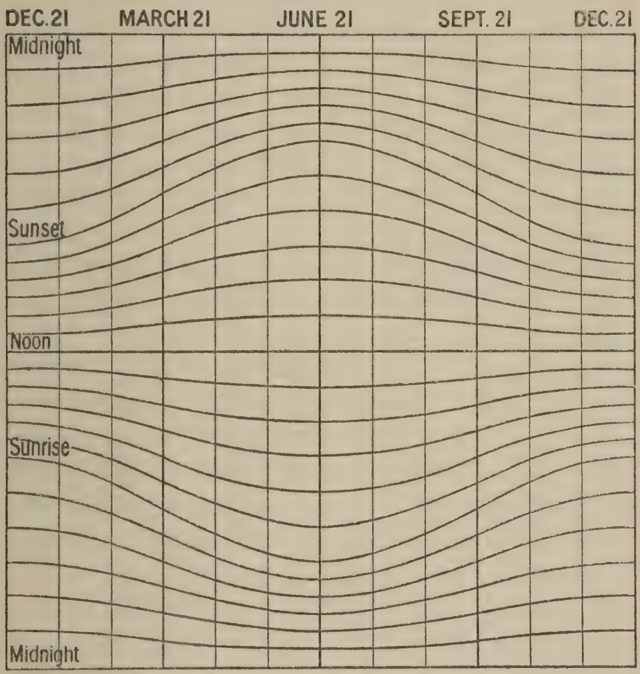


FIG. 10.—GRADUATION CURVES OF CLOCK OF KTESIBIUS.

aspects to the pointer, give the correct hour graduations for every day of the year. The curves are different for different latitudes, the particular ones shown being for a latitude in which the sun rises about 8 A.M. and sets about 4 P.M., modern reckoning, in winter, and rises about 4 A.M. and sets about

8 P.M. in summer. A corresponding chart for places on the equator would consist merely of 24 equidistant and horizontal straight lines. The reader may amuse himself by thinking out how the Greek way of reckoning time would answer at the poles, or anywhere within the Arctic or Antarctic circles. The armillary sphere will help him.

In another form of Clepsydra the float is connected to a cord which takes a turn or two round the axle of a pointer for indicating the time on a dial. In this case the flow of water is regulated by hand according to the time of year, an indicator being provided which is set to the proper sign of the zodiac marked on a dial, and there are many other varieties.

Sand Clocks. Time measures in which sand is used instead of water are free from the defect of unequal flow due to varying depth, since the rate of flow of sand through an orifice depends only upon the "angle of repose," which is the steepest possible slope of the sides of a pile of sand, an angle which is independent of the size of the pile.

The hour glass is the most familiar form of sand clock. It consists of two pear-shaped glass bulbs connected at their smaller ends by a narrow neck, through which sand trickles from one bulb to the other when the common axis of the bulbs is vertical. When all the sand has run out of the upper bulb, the apparatus is turned upside down and the sand runs back again. Sand clocks may, of course, be made so as to indicate any length of time besides hours.

Lamp and Candle Clocks. Embodiments of the idea of utilizing the amount of oil burnt in a lamp for measuring time have been in use down to recent times.

Alfred the Great used candles as rough time indicators. Asser, Bishop of Sherborne, Alfred's friend and biographer, tells us that the king devoted a very considerable part of each day to pious exercises, and in order to apportion the time he kept graduated candles constantly burning before the sacred relics which he always had with him wherever he went. The candles were of wax, twelve inches long and graduated in inches. They burnt for four hours each, and were enclosed in lanterns made of wood and thin translucent plates of horn to prevent them from guttering in the wind.

The Sun-dial. The origin of the sun-dial is as obscure as that of the Clepsydra. The earliest reference to one is to the dial of Ahaz mentioned in II. Kings xx. 8-11, and Isaiah xxxviii. 8, in the accounts of the healing of King Hezekiah by the prophet Isaiah. It has been conjectured that this instrument might have been imported from Babylonia, but nothing is really known about it.

The earliest form appears to have been the gnomon, which was a simple vertical stake or obelisk casting a shadow, the position of which indicated the time. It is stated [1] that the Greek sun-dials did not indicate the hours before the fourth century

[1] *The Book of Sun-dials*, by Mrs. Alfred Gatty (G. Bell & Sons). Those who are interested in the history and the varieties of sun-dials should consult this very curious and interesting book.

B.C., also that the Romans adopted dials from the Greeks, the first dial having been set up in Rome in 293 B.C.

The sun-dial in its simplest form consists of a plate, usually horizontal, in the centre of which is fixed the *gnomon* [1] or *style*. This is a rod or bar parallel to the earth's polar axis and often forming one side of a triangular piece of sheet metal. The sun, as it moves round in the course of the day, casts the shadow of the style on the plate or dial and indicates the time on the dial, which is graduated in hours. It is not necessary for the dial to be either flat or horizontal. In fact, it may be of any shape or fixed in any position as long as it catches the sun. Plate I. shows a cluster of sun-dials arranged in different positions, and it will be noticed that the styles of all of them are parallel to one another and to the polar axis of the globe at the top.

The sun-dial, as stated in the last chapter, indicates true solar time, and its principle can easily be understood by reference to the armillary sphere. This instrument can, in fact, be used as a sun-dial if the rod representing the polar axis is clamped so as to be parallel to the polar axis of the earth. This can easily be done with the help of a pocket compass and a clinometer [2] improvised out of an ordinary protractor scale and a spirit level, as shown in

[1] Not to be confounded with the gnomon mentioned above. A gnomon in the most general sense is a rod or post in any position intended to cast a shadow. The gnomon of a sun-dial is always parallel to the earth's polar axis.

[2] Clinometer or inclinometer: an instrument for measuring gradients.

[Reproduced by courtesy of Mrs. Douglas

CLUSTER OF SUNDIALS AT BEDALES, LINDFIELD, SUSSEX

Fig. 11. By means of these the rod can be adjusted so as to be in a vertical plane facing due north and south, and at an angle to the horizontal equal to the latitude. The horizon disk can be used to represent the dial and may be turned so as to face in any direction. When thus used, it has, of course, no necessary relation to the latitude, and the meridian wire has no significance. The rod forms the gnomon. If the cage be set so that any hour circle, say XXIV, is due south, the sun when due south, at whatever

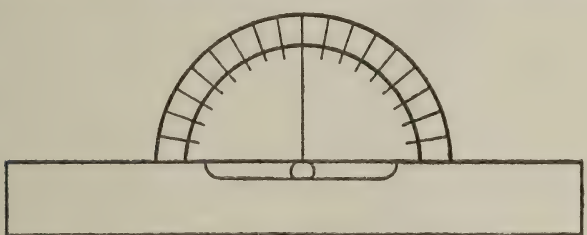


FIG. 11.—IMPROVISED CLINOMETER.

season of the year, will cast the shadow of the rod on the point of the dial crossed by the opposite hour circle XII. This is the noon point. Similarly for the other hours. For example, at 10 o'clock A.M. the sun will be opposite the hour circle II, and the shadow of the rod will fall on the intersection of the dial and the hour circle XIV. This intersection is, therefore, the 10 o'clock point on the dial. This will happen whatever the position of the dial or the sun's declination, but only if the rod be set parallel to the polar axis. It is on account of the necessity for this setting of the style that sun-dials are sometimes found with the styles set askew on the dial, and that

no ordinary sun-dial will indicate the time properly if not used in the latitude for which it was made, without re-setting the gnomon and re-graduating—re-making the whole apparatus, in short. Of course, sun-dials made after the pattern of an armillary

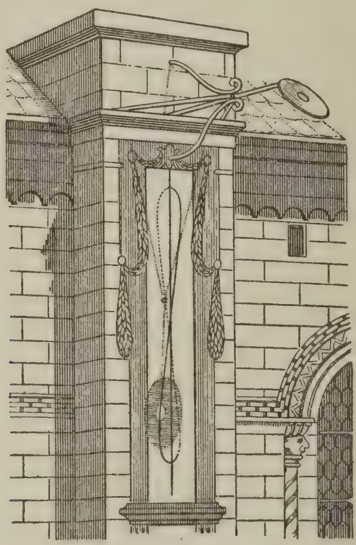


Fig. 12.—Meridian Dial.
(From Britten's *Old Clocks and Watches and their Makers.*)

sphere are adjustable for any latitude, and many portable forms have been designed.

A form of sun-dial called a *meridian* dial is sometimes met with, the object of which is to indicate noon only, not to give the time continuously. If a dial is intended merely for this purpose no attention need be paid to the polar parallelism of the style. A vertical post—a gnomon in fact, of the kind first

mentioned in this section—will answer the purpose quite as well. But to use a post in any position other than parallel to the earth's axis for continuous indication, a special scale is required for each pair of days when the sun's declination is the same.

Fig. 12 shows a meridian dial at St. Peter's Cathedral, Geneva. A hole in the middle of the sloping plate shown near the top of the picture throws a spot of light on to the vertical line on the wall at true noon. The curiously shaped long figure-of-eight curve is a form of the graph of the equation of time, and when the spot of light falls upon this curve mean noon is indicated. The dark oval on the vertical wall is the shadow of the sloping disk. Ordinary sun-dials are sometimes modified by shaping the style suitably so as to give mean time at any hour.

CHAPTER V

THIRTEENTH AND FOURTEENTH CENTURY CLOCKS

THE word *clock* is akin to the French " cloche " and the Welsh " cloch," both of which mean a *bell*, and thus etymology supports the tradition that the principal part of many at least of the early clocks was the striking mechanism. Some, indeed, seem to have had no other means for indicating the time. The word, however, has acquired the secondary meaning of an apparatus for giving a continuous indication of the time, and more particularly that class of apparatus which consists of a train of wheels driven by a spring or a weight.

The history of weight-driven clocks is as obscure as that of clepsydrae or of sun-dials. They come suddenly into notice about the end of the thirteenth century in a very advanced stage as regards design, though the workmanship was rough. Their previous evolution must have taken a long time, but there is no reliable record of its stages nor of the men responsible for it. The name of Pacificus, Archdeacon of Verona, who lived about 850 A.D., has been mentioned amongst others as the inventor, but we

are not told even where he erected his clock, much less its details.

Perhaps the most interesting personage credited with the invention of clocks is Gerbert, a French Benedictine monk. Gerbert's claims were pressed strongly by Father Alexander, another French Benedictine monk in a book [1] published in Paris in 1734. But as this was more than seven centuries after Gerbert's death, the evidence is of little value. Gerbert was certainly a remarkable man. He studied astrology and mathematics in Spain, where he came into contact with the Saracens, and is said by William of Malmesbury, writing a century or so after his death, to have introduced into Western Europe the Saracen system of numerals which we use at the present day. After serving in some important educational offices, he became Archbishop of Rheims in 992, Archbishop of Revenna in 997, and finally Pope under the name of Silvester II. in 999. But beyond his probable competence and the fact that he set up at Magdeburg a time-piece of some kind, which a third French Benedictine monk, William Marlot, who lived in the sixteenth and seventeenth centuries, believed to be so ingenious as to have required the help of the devil for its invention, nothing is known of his clock-making activities. Some, indeed, suppose with much probability that his Magdeburg time-piece was nothing more than a sun-dial, and there is good evidence that he was an expert dialist.

[1] *Traité Général des Horloges*, by the Rev. Father Dom Jacques Allexandre (*sic*), pp. 15, 16.

But setting aside speculation, it is certain that a number of clocks were made in the thirteenth and fourteenth centuries, both on the Continent and in England. Their history in this country commences in the reign of Edward I. with a clock which was set up at Westminster out of the proceeds of a fine levied on a corrupt Lord Chief Justice. Another was set up in Canterbury Cathedral in 1292, and these were followed by others at Exeter, Peterborough, Glastonbury, Dover Castle, Wimbourne, Wells, Ottery S. Mary, and elsewhere. The dials of several of these still exist, but the works of only a very few. They are, however, sufficient to show the probable construction of them all, which bears a strong, even a striking resemblance to present-day practice. The Wells clock dates from not later than 1393, and the works are still going in the South Kensington Museum. The Dover Castle clock, which is said to date from 1348, is also at South Kensington.

Something more will be said about these two clocks later on and pictures of them from photographs will be given, but these pictures, though sufficient to give an idea of the general appearance and workmanship, are unsuitable for explaining how they went. No description or drawings suitable for this purpose being available, use will be made of an illustrated description of a clock of contemporary date given by a French writer named Moinet.[1] Moinet tells us that his account was obtained from unpublished papers left by Julien Le Roy, a distin-

[1] L. Moinet, *Nouveau Traité Général d'Horlogerie*, Paris, 3rd edition, 1875.

guished French clockmaker, who lived between the years 1686 and 1759. The clock, or at least its works seem to have been destroyed since, but they were extant in Le Roy's time.

"Charles V., called The Wise, King of France," says Father Alexander, one of the Benedictines above mentioned, "caused to be made in Paris the first large clock by Henry de Vic,[1] whom he caused to be brought from Germany, and put it on the tower of his palace about the year 1370." This was in the reign of Edward III., about the time when the Black Prince was ravaging Southern France. Plate II. shows in front and side elevation the "going" mechanism, that is, the works which move the hands, or whatever alternative *visible* means were used for indicating the time. Of these means there were many varieties in the early clocks, such as rotating disks with numerals on them, globes, and the like. We reserve for a future chapter the striking mechanism, which though perhaps even more impressive as showing the advanced state of mechanical knowledge in the Middle Ages, is so distinct as to justify separate treatment.

Round the wooden barrel *A*, which is about a foot in diameter, is coiled a rope attached to a weight *B*. The barrel is secured to a large toothed wheel *C*, which engages with a pinion[2] *D*, the arbor[3] of which is squared to receive the winding handle. The weight, it may be remarked, weighed 500 pounds, or

[1] Also written Wieck, Wyck, and Wick.

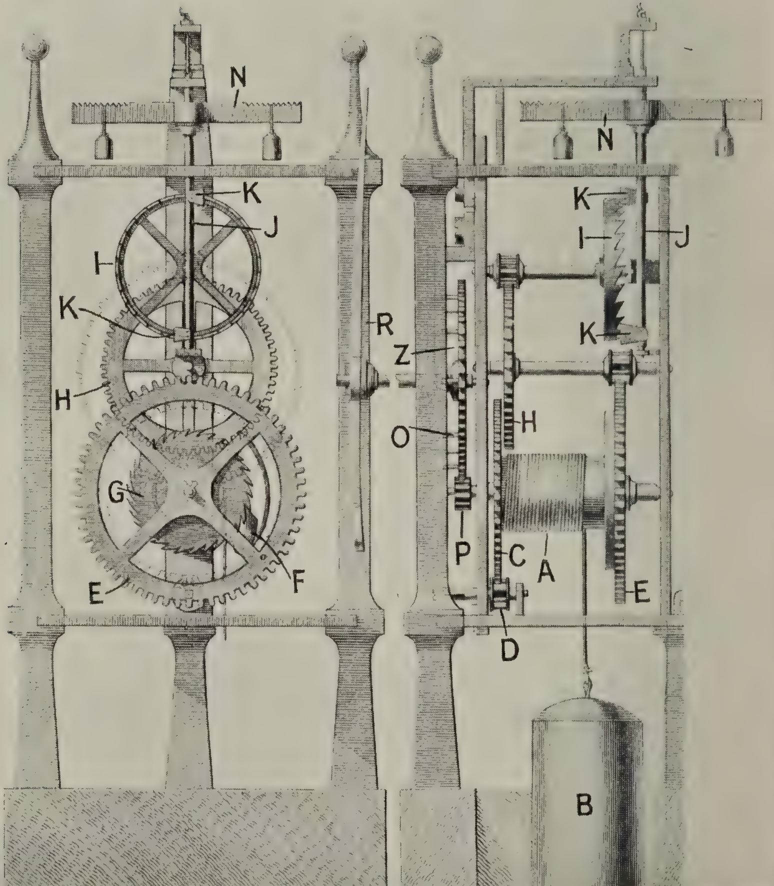
[2] A pinion is a small wheel having comparatively few teeth.

[3] Arbor is the clock-maker's word for the axle of a wheel. Cf. axle *tree*.

close on a quarter of a ton, and fell 32 feet in 24 hours. This, however, was far exceeded by the striking weight, which approached three-quarters of a ton. These immense weights were required partly by the rough workmanship of the mechanism, a feature which is not evident from the present drawings, but which will appear much more clearly in the pictures of the Wells and Dover Castle clocks. All the parts of these clocks were evidently made on the anvil by a blacksmith. The friction between the working parts must have been enormous. The great weight is also in part due to the type of escapement used and also to the size of the wheels. Some of the wheels in the Wells clock look to be three feet in diameter, and the size of those in De Vic's clock can be judged from the diameter of the barrel already given.

The barrel and the winding wheel *C* are mounted freely on the arbor of the great wheel, or first wheel, *E*,[1] with which the barrel is connected by a pawl *F* and ratchet wheel *G*. It is not necessary to describe this device in detail, since it is in common use, amongst other things for winding up the cords of lawn tennis nets. The effect of this connexion is to allow the barrel to turn without actuating the great wheel while the clock is being wound, but to compel the wheel to turn with the barrel when the weight is in action. The great wheel drives a pinion on the arbor of which is the second wheel *H*, and this in turn drives a pinion on the arbor of which is the

[1] These names are the technical ones for the first wheel of the train driven by the weight or spring.



REAR SIDE

DE VIC'S CLOCK. GOING TRAIN

Side and Rear Elevations. After Moinet

third or 'scape[1] wheel *I*. This last wheel is called a crown wheel, since its teeth project sideways. They are formed like those of a saw in order to enable the wheel to take its part in a device for controlling the speed called the *escapement*, which converts the machine from a mere train of wheels into a proper piece of clock work.

The escapement is one of the most difficult parts of the clock to describe, and wants to be seen to be appreciated properly. However, on account of its essential character the attempt must be made. A vertical spindle *J* called a " verge "—probably from the Latin *virga*, a rod or twig—stands diametrally across the crown wheel. Its lower end rests on a bracket, while its upper end is suspended by a cord which helps to take the weight off the bracket. It is provided with two small leaves or plates *K*, *K*, called *pallets*, opposite the teeth at the top and bottom of the crown wheel. The pallets are set at right angles to one another, or a little more, and engage alternately with the teeth of the wheel. When, for example, the steep side of a tooth at the bottom of the wheel encounters the corresponding pallet it pushes the pallet to one side, thereby turning the verge on its axis and causing the upper pallet to enter the gap between two teeth at the top of the wheel. When the lower pallet has been entirely pushed aside so that the acting tooth can pass it, the wheel, and therefore the whole clock mechanism, advances with a little jump, which, however, is soon checked by the contact of the upper

[1] Short for escape or escapement.

pallet with the steep side of one of the adjacent teeth. The pressure of this tooth now reverses the rotation of the verge, and the whole process is repeated, the motion of the verge being continually reversed and a tooth of the crown wheel released each time. To prevent this motion from proceeding too fast the verge carries a crossbar or *balance* [1] *N*, with adjustable weights for regulating the rate of oscillation ; the farther the weights from the verge axis the slower the oscillations.

A feature of this escapement mechanism is the recoil which it produces in the clock train. When a pallet encounters a tooth of the crown wheel the motion of the verge is not stopped instantly, owing to the momentum of the crossbar and weights. Some little time elapses before the motion is stopped and reversed, during which time the crown wheel is forced round slightly in the opposite direction to that in which the driving weight *B* urges it. The motion of the whole train is thus to a slight extent reversed, and the driving weight raised at every escape of a tooth. This effect is technically called *recoil.* It is an imperfection of the mechanism, for though the power expended in lifting the clock weight is partly recovered by the subsequent fall of the weight, it is not wholly or even largely so, on account of the friction in the train and the loss in reversing the wheels and the balance.

The gear ratio of the train—an expression too well

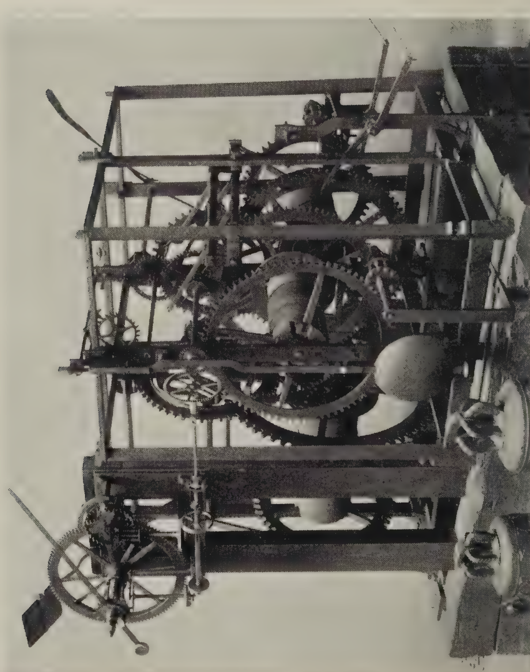
[1] Called a " foliot " for some reason with which the writer is unacquainted. By an error in the drawing a full view of the balance appears in both figures, giving the impression that it has four arms. It has, in fact, only two.

understood in these days of motor cars and geared cycles to require explanation—is such that the great wheel *C* rotates once an hour. On its arbor is fixed a pinion *P* with eight teeth, in gear with a wheel *Z* of ninety-six teeth, which therefore rotates once in twelve hours, and on or connected with the arbor of the wheel *Z* is the hand *R*, of which there is only one, corresponding to the hour hand of our modern clocks. The minute hand was not generally introduced as a common feature until a much later date. The pins *O* on the wheel *Z* relate to the striking mechanism, as will be seen later on.

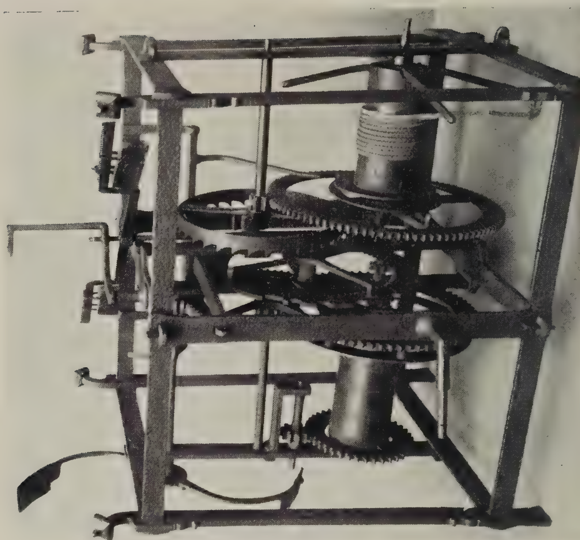
Some authorities consider that the verge escapement just described was not the governing mechanism originally used for the going train of very early weight-driven clocks. It is thought that the earliest of these were governed by the action of the air on a fan, such as is used for musical boxes, and was, and still is, used for the striking trains of clocks, but none of the writers who express this opinion produce any evidence for it. It is not necessary to say more at present about this mode of regulation, as further reference will be made to it in the chapter on striking mechanisms. It is certain, however, that the verge escapement was used for clocks for at least 350 years, down to the latter part of the seventeenth century, when it was displaced by the anchor escapement, of which more hereafter, and it was used in a modified form for watches down to a much later date.

The Wells Clock. The great clock of Wells Cathedral was made not later than 1392, probably by Peter Lightfoot, a monk of Glastonbury, or by

some immediate successor of his. It strikes the hours and the quarters, and the dial shows the hours and minutes and the age and aspects of the moon. In addition to which various performing figures are actuated, some of which strike blows on bells at the quarters and hours. Such figures as these last, called " Jacks," were a usual feature of old clocks. The old works, with certain parts altered, are now in the Western Galleries of the Science Museum, South Kensington, and are still going and striking. The dial and the performing figures remain in Wells Cathedral, fitted with modern works but giving the old indications. The works are shown in Plate III. The iron frame is square in plan and is divided into three main compartments, one for the going train, another for the quarter striking train, and the third for the hour striking train, each driven by its own weight but all interconnected. The going train, which alone concerns us in this chapter, occupies the front right-hand compartment as seen in the picture. A hand which did not belong to the original clock is seen on the left, and is connected with the going train by mechanism which extends along the front of the clock. This mechanism is new, as are also the pendulum and the escapement, the latter of which is of the recoil anchor type to be described elsewhere. Originally, without doubt, a verge escapement and balance governed the speed. The mechanism is the same in principle as in De Vic's clock, but it is somewhat more elaborate, there being one more large wheel. This additional wheel rotates once in half an hour, and the whole of the



WELLS CLOCK



DOVER CASTLE CLOCK

Reproduced by kind permission of the Directors of the Science Museum, S. Kensington

dial and hand mechanism is driven off its arbor, the arbor being geared to the front horizontal shaft, off which the several motions are taken. As has been stated, this shaft is new, but there must have been something corresponding to it originally, as is clear from the remains of the old mechanism, seen near the left hand of the picture. The workmanship is very rough but substantial and business-like, and a credit to the old monk who designed and made it.[1]

The Dover Castle Clock. Not far from the Wells clock in South Kensington stands a decrepit veteran from Dover Castle. It is said to be of Swiss make and to date from 1348. The going part is still occasionally set to work for the edification of the curious. It is shown in Plate III. It is smaller than the Wells clock, the frame, which is rectangular in plan, measuring about 28″ by 20″. Its construction also is simpler, since the great wheel drives the pinion on the 'scape wheel arbor directly, the second wheel being omitted; also the hours only were

[1] Until recently a tradition was commonly accepted that this clock is the original Glastonbury Abbey clock which was made by Peter Lightfoot about 1335 or 1340. The tradition had it that Lightfoot's Glastonbury clock was removed to Wells Cathedral at the time of the dissolution of the monasteries by Henry VIII. But the Chapter Rolls of Wells record over a long series of years, extending through the fifteenth century back to 1392, the existence of a clock in Wells Cathedral, and there is nothing to show that the present clock is not the same. Those who desire to go further into the matter should read *Peter Lightfoot and the old Clock at Wells*, by R. P. Howgrave-Graham (Avalon Press, 27 High Street, Glastonbury); also a paper by the Rev. Canon C. M. Church in the Somerset Archaeological Society's Proceedings, 1909 (vol. lv. p. 97). A *résumé* of the story of this clock was given in an article by the Dean of Wells in the *Observer* of May 20, 1923. These publications also describe such parts of the original clock as remain at Wells.

struck. In the present state of the clock the 'scape wheel turns once in about 4 minutes, which causes the great wheel to rotate once in about 55 minutes. No doubt originally it rotated once an hour. There may have been some gearing between the great wheel arbor and a hand, but if so it is now missing. The balance bar, which appears clearly at the top of the picture, is about 32 inches long and takes 7 or 8 seconds to perform one complete oscillation to-and-fro. The arc of oscillation seems to vary periodically in the course of an hour from 50° to 70° and back again, the average swing being about 60°. It is now impossible to say whether this was always so, or whether it is the result of old age. It would, of course, make the clock a bad timekeeper over short periods, say of an hour or so, but doubtless matters would average themselves out fairly well in the course of a day. There is a remarkable steadiness and absence of jerk in the oscillations of the balance, and the recoil in the mechanism while the bar is being brought to rest is less than might be expected, but the work expended must be considerable. The bar turns through about 10 or 15 degrees from the time when a tooth strikes a pallet until it is brought to rest. There are many marks of careful design about this old machine which would not disgrace a modern drawing office. The particulars would hardly appeal to the general reader, but it is refinements of this kind rather than the appearance of a machine which impress the mechanician. To those who have the training to perceive it, there is in these early clocks evidence

of a state of knowledge far in advance of anything to be gathered from general histories. Even if the histories told us, which they seldom or never do, that clocks or other machines were made in those days, the information would be of little value as showing the state of progress without telling us something about their construction. Let us, therefore, take off our hats to those like the maker of the Dover clock and Brother Peter Lightfoot of Glastonbury, monk and blacksmith, who with their charcoal forges and anvils have left a record showing an aspect of those times more humane than much which appears in the chronicles.

CHAPTER VI

GALILEO AND HUYGENS

We now skip over some three centuries, from the latter end of the fourteenth century, marked for us by the French Wars of Edward III., to about the middle of the seventeenth century, when things were coming to an issue between Charles I. and his Parliament. During all this time the balance described in the last chapter was in use, and little advance was made in general design.

The next step was the introduction of the pendulum as a means for governing clocks, meaning by *pendulum* a heavy body, not necessarily rigid nor even wholly solid, which swings to and fro freely by its own weight about some point of support. It has been seen that the whole burden of reversing the old balance was thrown on to the driving weight and the going train, and it may readily be imagined that the introduction of a device which reversed itself and left the clock train little or nothing to do but to move the hands had a radical effect on clock design. It is by no means certain, however, that this self-reversing property of the pendulum was the one which attracted most notice at first; in fact,

the verge with its pallets which remained in use was hardly calculated to take full advantage of it. What we hear of chiefly about the pendulum is its supposed isochronism, that is to say, it was believed always to swing in the same time, though the arc through which it swung might vary. Bearing in mind what was said in the last chapter about the varying angle of oscillation of the balance bar of the Dover clock, the advantage of a device which would keep time notwithstanding such irregularities is obvious.

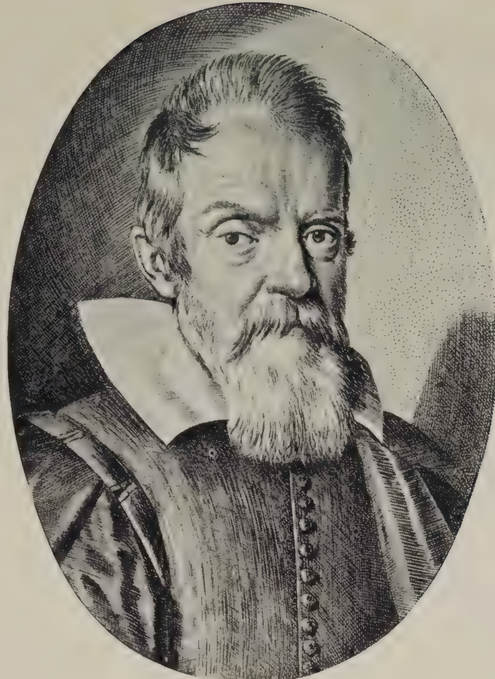
It is not proposed here to attempt to trace the origin of the pendulum. Some say that the Spanish Saracens were acquainted with it, and it seems certain that Tycho Brahe, the astronomer of Prague, and master of Kepler who has already been mentioned, as well as other astronomers, used it for measuring, or rather counting short intervals of time. Nor shall we discuss the question who first applied it to clocks as a speed-governing means, though this matter was once hotly debated. The seventeenth century, which was remarkable for so many scientific discoveries, was also remarkable for the number of somewhat sordid squabbles about priority in those discoveries. Rivalry of this sort may be unavoidable where money interests are concerned, but they are out of place in science.

It seems certain that Galileo was the first to direct attention to the isochronic property of the pendulum, by which is meant not merely that the same pendulum always swings through the *same* arc in the same time, but that it swings through *different*

arcs in the same time. This is true to a fairly close degree of approximation when the arcs of swing are small, though, as we shall see, the isochronism is not exact. This celebrated physicist, whose full name was Galileo Galilei, was born in Pisa in 1564 and died in 1642. Perhaps he is best generally known for his championship of the heliocentric theory of the solar system, about which he had the misfortune to differ from the ecclesiastical authorities, but it may be surmised that his powers of caustic though not unkindly irony had as much to do with getting him into trouble as his opinions. The following story throws some light on this side of his character. Having been asked why it was no longer possible to cook eggs in the Babylonian manner, which was to whirl them round in slings, he said that there must have been some difference in the circumstances, and the only discoverable difference being that the cooks were Babylonians, the alleged effect must be due to that fact. His contributions to science were very great. Amongst other things he discovered the true connexion between the motion of bodies and the forces acting upon them. He also made an improved telescope from a description which came to him of a crude Dutch instrument, and with this he made many astronomical discoveries, amongst them the four greater satellites of Jupiter.

The story goes that Galileo when a youth noticed that a lamp pendant hanging from the roof of Pisa Cathedral oscillated in the same time whatever its extent of swing. He is said to have timed the

Plate IV



GALILEO

From the engraving by Ottavio Leoni (1625)

CHRISTIAN HUYGENS

From Huygens' "Opera Varia"

oscillations by his pulse. There is a somewhat unconvincing picture commemorating this discovery in which Galileo is represented as a stripling standing in an almost empty church looking towards the roof with a rapt expression and feeling his pulse. But while we may well believe that the discovery was made in a church, we may be permitted to doubt whether the picture is accurate in other respects. We prefer to think that it was an ordinary case of inattention during Service, an occurrence which, though common enough, is not always attended by such happy results. Galileo used the pendulum for timing physical experiments, and he published his researches upon it in 1639. Curiously enough, he never actually applied the pendulum to the control of a clock, unless this name can be given to a clock-work machine, the object of which was to keep a pendulum swinging by preventing the friction of its pivot and the resistance of the air from bringing it to rest. He never made the machine, but when he was old and blind he dictated a description of it to his son, Vincenzio Galileo. A model of it at work is in the South Kensington Museum. Neither he nor his son apparently ever thought of putting a hand on it so as to enable it to tell the time, and the incident is a remarkable case of how near a man may get to a great invention without actual attainment.

Undoubtedly the man to whom is due the introduction into general notice of the pendulum as a clock governor was Christian Huygens van Zulichem, commonly called Huygens. He was a

student of the University of Leyden, and one of the foremost mathematicians and natural philosophers of this time. He also, like Galileo, improved upon the telescope, and by means of it he solved the problem of the strange protuberances on Saturn which had puzzled previous astronomers, showing that they were, in fact, rings surrounding the planet. His contributions to the subject of light are too technical for present discussion, but he may be said to be the founder of the modern wave theory.

Huygens found out that the isochronism of Galileo's pendulum was approximate only. It is very nearly exact for small arcs, say up to two or three degrees, but for larger arcs the divergence becomes impossibly great. Two courses are thus suggested; either to keep the oscillations always as nearly as may be to the same arc, which must be small so that such irregularities as arise shall count for as little as possible, or else so to modify the pendulum itself as to make it isochronous. At this stage of the development of clock construction the first alternative was impracticable, since no escapement other than the verge was known, and this required an arc of oscillation much too large for even approximate isochronism. Huygens therefore chose the second alternative and embodied his ideas in the clock shown in Fig. 13, which is a reproduction of a drawing in his book *Horologium Oscillatorium*, published in Paris in 1673. The rod *VV* of the pendulum, as shown in "Fig. I." and "Fig. II." of Fig. 13, is suspended by two parallel cords between plates *T*, against which the

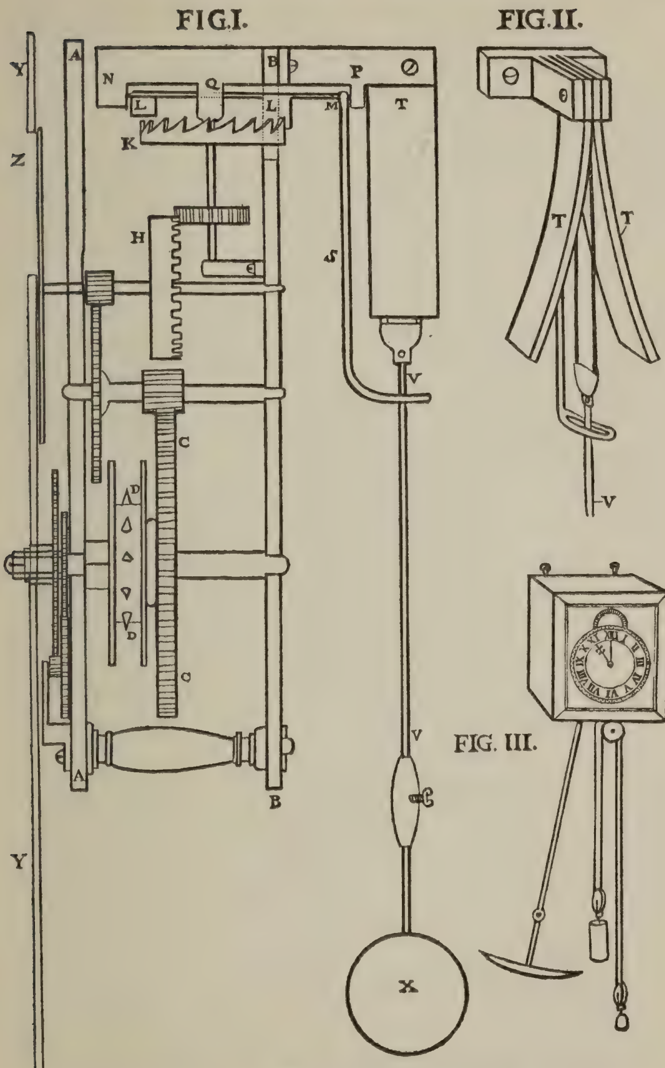


FIG. 13.—HUYGENS' CLOCK. (From Huygens' *De Horologium Oscillatorium.*)

cords bear alternately at each swing, and which are curved to the shape of a special curve called a *cycloid*.[1] The object of having two cords is to ensure that the pendulum shall swing in one plane. Huygens believed that this mode of suspension realized with sufficient accuracy the conditions to which his mathematical researches had led him. The rod has a heavy bob *X* at its lower end, and just above the bob is an adjustable weight for regulating the time of swing. Near its upper end the rod passes through a slot in the horizontally projecting end of the arm *S*, which is attached to the verge at *M*. This mode of connecting the pendulum to the escapement is substantially the one still in use. The verge is pivoted in supports *P* and *N*, and is further supported near its middle at *Q*. *L*, *L* are the pallets. The verge and 'scape wheel *K* are in this instance horizontal, but the going train is in other respects substantially identical with that described in the last chapter. The driving drum or barrel *D* is spiked to receive the weight cord. This is applied in a special manner which does not concern us at present.

It is not asserted that this clock was the first to which a pendulum was applied. Probably not ; our information is too meagre to warrant any positive statement on that point, but this was the first clock for which we have clear and positive evidence of its

[1] This curve is that which is described by a point on the tyre of a wheel as it rolls on the ground. It resembles a series of arches, each arch corresponding to a complete rotation of the wheel. Its properties need not be discussed here, but any one interested in them can find them in almost any book on mechanics.

use. Huygens' pendulum, however, is far from realizing all the theoretical conditions for isochronism. The chief of these, which is that the oscillations should be absolutely free from outside interference, is obviously not satisfied, for though the pendulum, unlike the balance, tends to come to rest of its own accord at the limits of its swing, it is still subjected to the same checking and reversing influences which, as has been seen, affected the balance. But it must not be concluded that it was because of this failure to reach the ideal that Huygens' cycloidal pendulum was applied to a few clocks only. The real reason was the comparatively accidental circumstance of the invention of the anchor escapement, which permitted the use of a pendulum with a very much smaller arc of oscillation. As long as the verge escapement was used a large arc was a necessity, and it is quite possible that, had no other form become available, clocks would have developed along Huygens' lines, and that we should still be using his pendulum, though doubtless in a greatly modified form. But as things turned out, the anchor escapement, which will be explained in the next chapter, made small arcs possible and opened the way to the first of the two alternatives mentioned a few pages back. Huygens' influence on clock construction was great, though probably for the most part indirect. The careful investigations of a man of his standing and attainments could hardly fail to bear results, though his concrete proposals may not have been those which actually prevailed.

The clock shown in Fig. 13 was a small one.

The plates *A*, *B* which support the mechanism are described as being about 6 inches in height by 2½ inches in breadth and about 1½ inches apart. It also possesses a feature which, though it has nothing to do with the pendulum, is of interest, since it is the mechanism used with but slight modification to the present day to provide for two hands. The older clocks, it will be remembered, had but one hand corresponding to the present hour hand. Huygens was the first to construct a clock with separate hands or indicators for minutes and seconds. The great wheel *C* rotates once an hour and carries on its arbor, which projects through the dial plate *Y*, a minute hand driven directly, and also a loosely-mounted hour hand driven from the minute hand by a twelve-to-one reduction gear. This gear is shown between the plates *A* and *Y*, and its effect is that the hour hand moves at one-twelfth the speed of the minute hand. The minute hand is merely friction-tight on the great-wheel arbor, so that the hands can be set independently of the internal works in the well-known way. *Z* is a plate which rotates once in a minute with the wheel *H*, and indicates seconds through a hole in the dial plate *Y*. This hole appears as a semi-circle above the dial in "Fig. III." which shows the outside appearance of the clock.

The arrangement of strings and weights also shown in "Fig. III." is an invention of Huygens, of which a clearer representation will be given in the chapter on Driving Mechanism, and the curious lens-shaped pendulum bob is a suggestion of his for reducing air resistance.

CHAPTER VII

HOOKE, GRAHAM AND HARRISON

The Anchor Escapement. The introduction of the anchor escapement, which made it possible to use a pendulum with a small arc of oscillation, was probably as important a step as any which has been made in clock construction. The date of its invention is given as 1675 and it is ascribed with but little doubt to Dr. Robert Hooke, whose name has come down to us chiefly in connexion with a law expressing the action of forces upon springs, and with a highly ingenious coupling for two rotating shafts not in line, a device which has since become one of the stock joys of examiners in mechanism, and a woe of students. This unlovely character, who nevertheless was one of the foremost scientific worthies of his day, was born at Freshwater, Isle of Wight, in 1635. After a period at Westminster School under Doctor Busby, famous for his faith in the rod as a pedagogic engine, he went to Christ Church, Oxford, in 1653. The Royal Society was granted its charter in 1662 and Hooke became a fellow in the following year. He held in connexion with it a lectureship on mechanics created for his benefit, and he was

also Professor of Geometry at Gresham College. No portrait of him seems to exist, and it is believed that he would never allow one to be taken. It is not certain whether he showed his good sense or his stinginess in this, for a note [1] we have about him says: "In personal appearance Hooke made but a sorry show. His figure was crooked, his limbs shrunken; his hair hung in dishevelled locks over his haggard countenance. His temper was irritable, his habits penurious and solitary. He was, however, blameless in morals and reverent in religion. His scientific achievements would probably have been more striking if they had been less varied. He originated much but perfected little." From this note the reader will not be surprised to learn that his name figures prominently with little credit to himself in many of the priority disputes of the day. The unhappy miser died in 1703, and after his death was found an iron chest, which did not seem to have been opened for years, containing several thousand pounds amassed while he was acting as surveyor to the works during the rebuilding of London after the Great Fire.

Hooke's anchor escapement is shown in Fig. 14. The crown wheel of the verge escapement is replaced by a wheel the teeth of which are in its plane. The pallets, which engage alternately with teeth some distance apart, lie in the plane of the wheel and are formed as a single anchor-shaped piece, from which fact the escapement derives its name. Under the

[1] *Encyclopaedia Britannica*, eleventh edition. Article, "Hooke, Robert."

influence of the pendulum the anchor oscillates about its pivot *A*, and the movement of the pallets necessary to free the 'scape wheel is very slight compared with that of the verge escapement But, on account of the wedge-like shape of their acting faces *B*, *C*, there is the same tendency to produce recoil and consequent interference with the free motion of the pendulum, though in a less degree. Still, this escape-

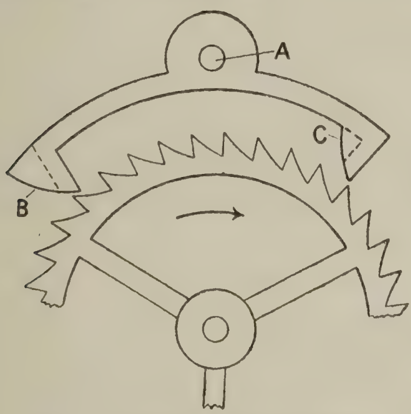


FIG. 14.—HOOKE'S ANCHOR ESCAPEMENT.

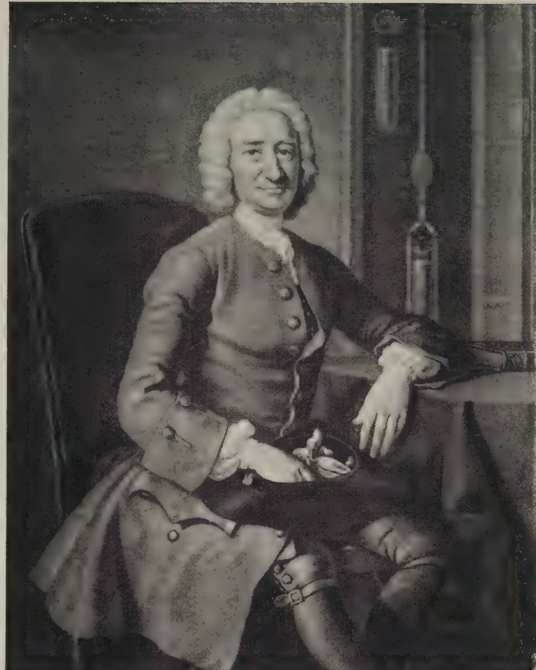
ment was a great advance on its predecessor, and it remains in use for ordinary house clocks and others in which refined accuracy is not required.

The recoil difficulty was met by a modification of Hooke's escapement, known as the anchor *dead beat* escapement. This was the invention of George Graham, clock-maker and one-time assistant of Thomas Tompion, who has been called "the Father of English watchmaking" on account of the perfection to which he brought the art, mainly by

careful attention to design. Before Tompion's time watchmakers thought more of the case than the works.[1] If the watch looked well and went in some fashion, *how* it went was not so essential. Graham was a man of considerable originality and character. Born in Cumberland in 1673, he tramped to London at an early age and served his apprenticeship to a clock-maker. His career with Tompion, with whom he took service, resembles in many respects that favourite of providence and of old-time moralists, the industrious apprentice. Graham was not actually apprenticed to Tompion nor did he marry his daughter, since Tompion was a bachelor. But he did the next possible thing. He married Tompion's niece and succeeded to his business. He became a Fellow of the Royal Society, and he and his master both lie in the same grave in Westminster Abbey. In 1838 the slab on which their work is commemorated was removed and replaced by a small stone square giving merely their names and when they died. Naturally, there was much soreness. Somebody wrote: "Who would suppose that a small lozenge-shaped bit of marble is all that is left to indicate where lie the bodies of the 'Father of clock-makers,' Thomas Tompion, and honest George Graham, greater benefactors to mankind than thousands whose sculptured urns impudently emblazon merits that never existed?" This and other protests having reached the ears of Dean Stanley in 1866, he replaced the original gravestone, which fortunately had not been destroyed. It was

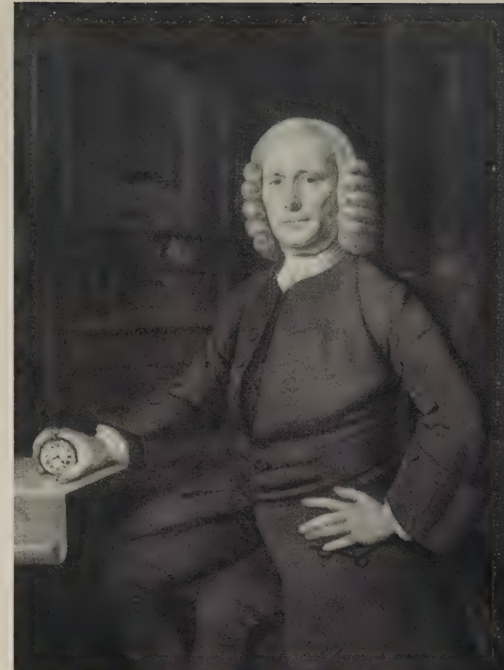
[1] Britten, *Old Clocks and Watches, etc.* already cited.

PLATE V



GEORGE GRAHAM

From the mezzotint by J. Faber after T. Hudson
(British Museum)



JOHN HARRISON

From the portrait in the Science Museum, S. Kensington

not without reason that Graham was called honest. "Securing to himself the monopoly of any of his discoveries was foreign to his disposition. The reputation which English horology acquired on the Continent during the eighteenth century was due in no small measure to Graham's candid treatment of his brethren in the art in other countries." [1]

Graham's improvement on the anchor escapement was simple enough, like a good many other great

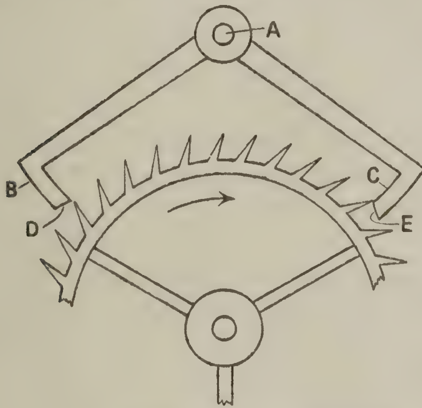


Fig. 15.—Graham's Dead Beat Escapement.

inventions. It is shown in Fig. 15. Instead of making the pallets wedge shaped with their acting faces of one continuous line, he cut away part of them along circular arcs having their common centre on the axis *A* of the spindle about which the anchor oscillates. The parts which Graham cut away are shown by dotted lines in Fig. 14. The effect is that when the teeth of the 'scape wheel encounter the

[1] Again we cite Britten.

faces *B*, *C*, Fig. 15, they simply lodge there without being driven back by wedging action. The pendulum is therefore free to finish its swing naturally, without any interference from the going train, except such as may arise from the friction between the pallet and the tooth. On leaving the tooth of the 'scape wheel the pallet receives on its uncut-away parts *D* or *E*, a small impulse or kick from the tooth, which is just sufficient to maintain the motion of the pendulum by counteracting the friction and air resistance. The escapement received its name " dead beat " from the fact that the 'scape wheel on striking a pallet stops dead and is not caused to recoil. For this reason also the face of the pallet on which the tooth lodges is called the *dead* face. One consequence of this is that a heavy pendulum bob may be used. In Hooke's anchor escapement a heavy bob would cause an excessive recoil.

This kick or impulse is a necessary function of all clock and watch escapements. In those described up to the present, the impulse required to keep the pendulum going is given by direct pressure of the 'scape wheel, and if this pressure should for any reason be irregular the motion of the pendulum will be irregular also. With the light machinery used in most clocks irregularities of this kind are insufficient to produce much effect if the pendulum is sufficiently heavy, but in large public or " turret " clocks as they are called, and in clocks used for very refined time-keeping, they may be serious. To meet this difficulty, what are called constant force or gravity escapements have been designed. In these

the pallets are detached from the pendulum and the greater part of their motion is derived not from the pendulum but from the going train. It would be beyond the purpose of the present book to give details of this type of escapement, of which there are several forms,[1] but the general effect is that at each swing the pendulum is acted upon by the weight of one or other of the pallets, which always drops through the same distance and thus gives constant impulses. Something more will be said about this type of escapement in the chapter on Electrical Clocks.

It will, of course, be understood that the escapements above described are merely types indicating the more noteworthy stages in the history of this class of mechanism. New forms are continually being invented.

Pendulum Suspension and Compensation for Temperature. In the earlier clocks the pendulum rod was fixed rigidly to the verge, but the mode now used is a modification of that employed by Huygens. Instead of two parallel cords a thin strip or a pair of strips of steel, like watch or clock spring steel, is used. Huygens' cycloidal plates are, of course, not required. The strip is clamped in a bracket either on the frame or on the case of the clock, or sometimes in turret clocks on the wall of the building in which the clock is installed. When anchor escapements are used, the connexion between

[1] Descriptions will be found in almost any book on clocks, *e.g.* Lord Grimthorpe's *Clocks and Watches and Bells*, or in the article " Clocks " in the *Encyclopaedia Britannica*.

the pendulum and the clock is exactly on the principle of the slotted arm employed by Huygens, shown in Fig. 13.

The refined methods of clock construction made possible by the use of the pendulum brought into prominence changes in the rate of the clock due to differences in temperature. A rise in temperature causes the pendulum to lengthen and the clock loses time, and a fall has the contrary effect. To counteract this, advantage is taken of the different expansion effects of heat on different metals. One of the best known embodiments of this principle is the "Gridiron Pendulum," invented by John Harrison, a famous clock-maker who, as will be seen later on, distinguished himself in connexion with the finding of longitude at sea. In the Gridiron Pendulum, one form of which is shown in Fig. 16, the main part of the rod is replaced by a number of parallel rods of steel and brass. *A* is the steel pendulum rod. *B* is a cross-bar carried by *A*, to which are attached vertical brass rods *C*. The upper ends of the rods *C* carry a cross-bar *D*, which supports vertical steel rods *E*. These last rods again carry a cross-bar *F*, to which brass rods are attached and so on, the bob, *G* being carried by a cross-bar attached to the outer pair of steel rods. In the result, the expansion of

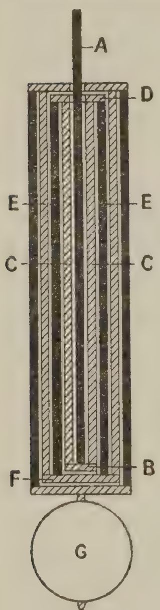


Fig. 16.
Harrison's Gridiron Pendulum.

the five steel rods downwards is counteracted by that of the four brass rods upwards—since brass expands more than steel for the same differences of temperature—and the pendulum always swings at the same rate. The object is not to keep the centre of gravity of the pendulum in the same position, as might be supposed, but to maintain the position with reference to the point of support of another point called the *centre of oscillation*, which is somewhat below the centre of gravity. The position of this point depends not only upon that of the centre of gravity, but upon what is called the *moment of inertia* of the pendulum about its point of support. The moment of inertia is a quantity obtained by multiplying the mass of each particle of the pendulum by the square of its distance from the point of support, and adding all this infinite number of products together. It is hardly necessary to say that this somewhat uninviting addition sum requires for its performance other means than the ordinary rules of arithmetic, but with these means it is not necessary to trouble the reader. Moments of inertia have many important practical applications. Engineers, for example, require them for problems relating to the balancing of engines and in calculating the strength of beams. But they come specially into account in all cases where there is swinging or rotation. For instance, the buyer of a tennis racket or a cricket bat or a golf club is not satisfied with trying its weight and balance. He swings it about to ascertain what it will probably feel like when used in

play. In so doing, he is, in point of fact, making a determination of its moment of inertia.

Another method of carrying out the same idea is to use a tall cylindrical vessel of mercury for the bob. This method was invented by Graham and is still in common use. When the rod lengthens in consequence of an increase in temperature the mercury rises in the vessel and thus keeps the period of oscillation constant.

It is an obvious advantage to make the rod of material which is little influenced by heat. Wood is frequently used for the purpose. A substance called "Invar," which is an alloy of nickel and steel and is almost unaffected by ordinary variations of temperature, is in extensive use.

CHAPTER VIII

STRIKING MECHANISM

The present chapter is concerned with the means by which a clock discharges its primitive duty of giving the time by strokes on a bell. Mechanism for effecting this may be of all degrees of complexity, from a simple device which gives a single stroke at each hour, up to elaborate carillon machines which play tunes at regular intervals. It is beyond the scope of this present book to describe anything so complicated as carillon mechanism, but it is hoped that the description which it is proposed to give will be a help to the reader should he desire to follow the matter up in technical treatises. There are certain types or principles which apply generally.

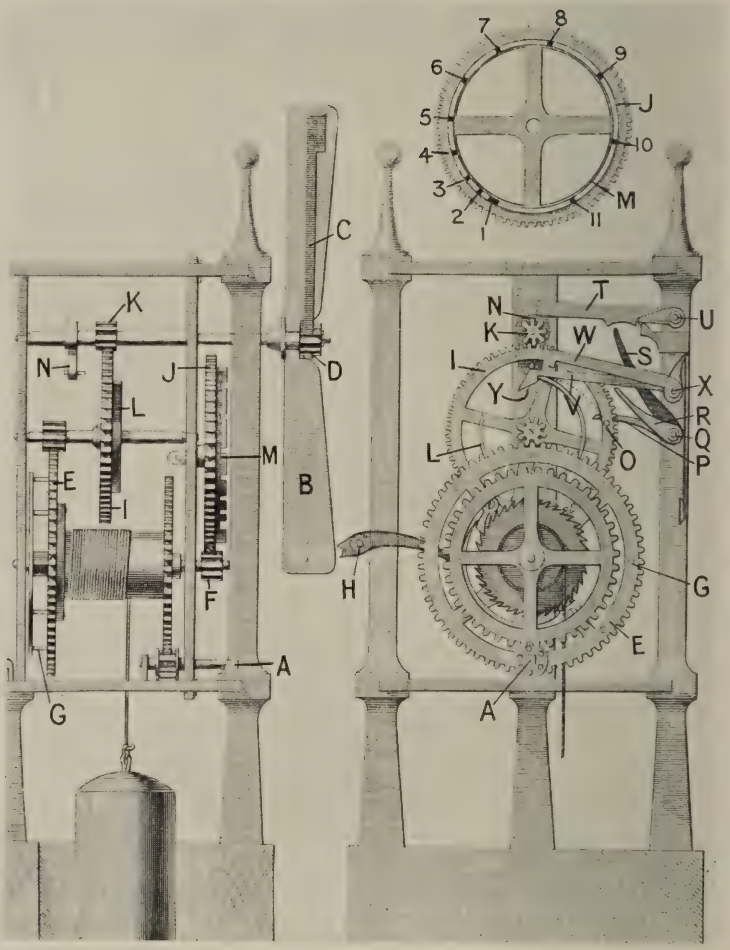
The simplest striking mechanisms in use are those which give strokes corresponding to the number of the hour, one stroke for one o'clock, two for two o'clock and so on, and of these there are two well-defined types, the counting wheel type, and the rack or repeating type.

Counting Wheel Type. This type, though the oldest known, is still in use, more especially in turret clocks. Modern forms of the mechanism differ con-

siderably in appearance from those used in the clocks described in Chapter V, but the principle is precisely the same. Plate VI. shows in side and rear elevation the striking mechanism of De Vic's clock as described by Moinet, to whom reference has already been made. The mechanism shown in Plate VI. (side elevation) joins on to the right-hand side of that shown in Plate II. of Chapter V.

The general lay-out of the striking train does not call for special description, as it is similar to the going train and is actuated in the same way by a weight which is wound up by a key applied at *A*. The governing mechanism is, however, different. In the present instance the restraint is effected by means of a fan *B*, which is loose upon its arbor but is caused to rotate by spring pawls *C* engaging with the teeth of a ratchet wheel *D*. Thus the wheel train, while running down, drives the fan which checks the motion by air resistance. When the wheel train stops, the fan runs on for a few turns, but is quickly brought to rest by air resistance and by the friction of the pawls upon the ratchet wheel.

Upon the arbor of the great wheel *E* is fixed a pinion *F* of eight teeth, and on the face of the great wheel are eight pins *G* which engage successively with the tail of a lever *H* and thus cause the clock to strike. The other end of this lever actuates the hammer which strikes the bell. The great wheel meshes with a pinion on the arbor of the second wheel *I*, and the pinion *F* with another wheel *J* of seventy-eight teeth. The gearing is such that the second wheel *I* rotates once for each tooth of the wheel



SIDE

REAR

DE VIC'S CLOCK. STRIKING TRAIN

Side and Rear Elevations. After Moinet

J, or, which is the same thing, the wheel *J* rotates once for every seventy-eight rotations of the second wheel. The wheel *J* rotates once in twelve hours, and as during this time the hammer in striking the hours from 1 to 12 inclusive must hit the bell seventy-eight times, each tooth of the wheel *J* and each complete rotation of the second wheel *I* correspond to one stroke. The second wheel drives the fly arbor by a pinion *K*, and it also carries on its face a circular hoop *L*, part of which is cut away so as to leave a considerable gap as shown clearly in Plate VI. (rear elevation). Upon the face of the wheel *J* is the counting disk *M*, as shown separately at the top of Plate VI. The counting disk has on its edge eleven notches numbered 1 to 11. Ten of these are of the same size, the remaining notch, numbered 1, being twice as large. The notches are unevenly spaced, so as to leave full parts between them of progressively increasing length starting from the notch 1. Upon the fly arbor is an arm *N* provided with a pin. The objects of these features will be explained subsequently.

All this mechanism is, of course, at rest in the intervals between striking, and is entirely separate from the going part of the clock. We now pass on to its connexion with the going part, by which it is started at every hour and stopped when the proper number of strokes have been delivered. The large wheel *Z* of the hand train, Plate II., which, it will be remembered, rotates once in twelve hours, has twelve equally spaced pins *O* projecting from its face, each pin corresponding to an hour. One of these pins

is shown in Plate VI. (rear elevation). It appears on the face of the wheel *I*, but this is an accident in the drawing. It does not belong to this wheel, but, as before stated, to the wheel *Z*, part of which is shown by dots behind the wheel *I*. These pins engage in succession an arm *P*, called by French writers the "pied de biche" or *hind's foot.* The hind's foot is carried on a long arbor *Q*, which extends from the front of the going part to the rear of the striking part, where it carries two other arms *R* and *S*. An end only of the arbor *Q* is shown in Plate VI. The object of the arm *S* is to lift a detent or lever *T* pivoted at *U*, though from the drawing, which is somewhat imperfect in this respect, it might appear scarcely capable of so doing. This, however, is the intention. The function of the detent *T*, which is called the *preparation detent,* is to catch the pin on the arm *N* at the proper moment, as will be explained presently. The function of the arm *R* is to lift two detents *V* and *W* which are both fixed on the same arbor *X* and move together. The detent *V* is called the *cock detent* from the shape of its head, which, as Moinet says, "bears a faint likeness to the head of that animal." The likeness is certainly not striking in the drawing, but the writer has seen cases in which it is much closer. The acting faces of the cock head are two; one of these projects at right angles to the arm *V* and is shown in engagement with one end of the hoop *L*, while the other, shown at *Y*, which joins on to the former, has a much lesser slope of 30° or 40° only. The other arm *W* is the *counting detent.* It terminates in a claw which, in the position

of the mechanism shown in the figures, rests in one of the notches 1-11 in the counting disk *M*. None of these detents appear in Plate VI. (side elevation), but of course the reader will realize that this omission is merely to avoid confusion in the drawing.

The action is as follows. The parts being in the position shown, the mechanism is restrained from movement by the engagement of the right-angled acting face of the cock head with the end of the hoop *L*, while the claw on the counting detent *W* rests in one of the notches in the counting disk *M*, whichever happens to be uppermost. One of the pins *O* on the hour hand wheel is shown about to engage with the hind's foot *P*. As the hour hand wheel revolves, the pin *O* lifts the hind's foot, raising at the same time the arms *R* and *S*, and, therefore, the preparation detent *T* and the detents *V* and *W*. When thus raised, the detent *T*, the end of which is bent at right angles from the plane of the rear elevation, Plate VI., comes into the path of the pin on the arm *N*, so as to catch it in its highest position when the arm revolves. Meanwhile, the cock head also rises slowly, and as soon as the end of the hoop *L* is freed from the right-angled acting face, the mechanism begins to move. The end of the hoop then slides on to the acting face *Y* of the cock head, and the arm *N* gives a half turn, but its pin is almost immediately caught by the end of the preparation detent *T*, thus preventing further movement of the mechanism. This action, called the preparation or warning, gives rise to the noise heard in clocks

shortly before they strike. The claw on the counting detent *W* is not necessarily lifted at this stage completely out of its notch, but its seat in the notch is sufficiently loose to allow of the slight movement of the mechanism which constitutes the preparation, although the counting disk rotates slightly in the process.

This state of affairs continues for some few minutes, the pin *O*, and therefore all the detents, rising slightly but nothing else happening until the pin *O* passes the point of the hind's foot *P*, which then suddenly drops. This is timed to happen exactly at the hour. The result is that the preparation detent *T* also drops, releasing the arm *N*, and therefore the whole train. The detents *V* and *W*, however, do not drop, since the sloping face *Y* of the former rides up on to the hoop *L*; in so doing it also raises the claw of the detent *W* out of the notch in the counting disk if it is not completely out of the notch already. Thereupon the mechanism proceeds to move, the wheel *I* rotating until the gap in the hoop *L* is again presented to the cock head, which would then drop into the gap were it not that the counting disk has meanwhile rotated enough for the notch to move away from the claw on the counting detent *W*, which therefore now rides upon the solid part of the counting disk separating each gap from the next. The cock head is thus prevented from engaging with the end of the hoop *L*, which proceeds to perform a second rotation, and so on until the next notch is presented to the claw on the counting detent. The cock head can now drop into the gap in the hoop and

so stop the mechanism, and when it drops the counting detent claw also drops into the notch. At each rotation of the hoop a blow is struck on the bell by one of the pins on the great wheel *W*. The intervals between the notches 1, 2, etc., on the counting disk increase progressively as before stated, each permitting one more rotation of the hoop, and therefore one more hammer blow, than the last. An exception should be noticed in connexion with the notch numbered 1. When the counting detent claw first drops into this the clock has just struck twelve, and since one o'clock corresponds to one rotation only of the hoop *L*, it is sufficient merely to widen notch number 1 to twice the width of the others in order to stop the mechanism after a single rotation of the hoop. This accounts for there being eleven notches only instead of twelve as might have been expected.

It may be asked why all this elaboration is necessary and whether something simpler could not be devised. The answer is that the need arises from the necessarily slow motion of the hour wheel of the hand train which originates all the movements. It might be possible, for example, to devise means whereby the striking train could be released at some instant while one of the pins *O* was pushing aside the hind's foot. But on account of the slowness of the motion this instant would be difficult to time exactly with the hands of the clock, and, moreover, for the striking to stop, it is necessary for the hind's foot to have returned to its normal position, and in the time required for this, many blows might have

been struck unless the interval between each blow were made impossibly long. The dropping of the hind's foot as the pin passes it, is on the other hand an instantaneous action and easy to time with the hands, so that none of these difficulties arise. We shall presently see that when the originating motion is taken off a rapidly moving wheel the mechanism is much simplified.

The Wells and Dover Castle Clocks. The construction above described [1] is a fair specimen of the practice of the second half of the fourteenth century, as is clear from a comparison with it of the Wells and Dover Castle clocks which were its contemporaries within a few years. The mechanism of the Wells clock follows it very closely, such differences as exist arising mainly from the fact that the Wells clock strikes the quarters as well as the hours. A wheel in the going train which rotates once every half hour carries two pins corresponding to the twelve pins *O*, and actuates a hind's foot in a similar way. Otherwise, the quarter mechanism is substantially identical with that already described, with the trifling exception that there is no separate preparation detent,

[1] Prior to the appearance of Moinet's book no complete description of De Vic's striking mechanism was available. Ferdinand Berthoud in his book *Histoire de la Mesure du Temps* (Paris, 1802) did his best, and perhaps a little more than was strictly justifiable, with an avowedly imperfect description of "an old clock" (unspecified), published by Julien Le Roy. But Le Roy, though he knew De Vic's clock well, *published* nothing specifically referring to it, excepting some particulars about its weights. The writer of the article "Clocks" in Rees' *Cyclopaedia* (London, 1819) follows Berthoud, and this description has frequently been copied since. But it cannot be considered authentic. Moreover, the mechanism described is so crude as to be doubtfully practicable. It is no proper example of the practice of the time.

an arm corresponding to *S* acting directly on the preparation pin. The arrangement of the pins *G* is, of course, different, since the quarters are struck on two bells, but this is merely a matter of providing two sets of pins and spacing them properly. The quarter-striking counting wheel which rotates once an hour, carries a single pin which discharges an hour-striking train, just as the pin in the going train discharges the quarter train. The hour train mechanism is much simpler than the quarter mechanism, this simplification being rendered possible by the fact that, although the wheel which discharges it turns once an hour only, its motion is intermittent, and when going it moves much faster than the hand hour wheel which discharges the quarter train. The preparation detent and pin can therefore be omitted. The counting wheel, the hoop and the cock and counting detents are provided as before.

The striking mechanism of the Dover Castle clock shows the same general features, but in a less developed form. Apparently it struck the hours only, and the hoop is replaced by a simple lug or projection on the second wheel, which in part served the same purpose. The absence of the continuous hoop makes the mechanism somewhat cruder.

The dates assigned to these old clocks by various writers are often vague and sometimes discrepant to the extent of eight or ten years. This is partly accounted for by the time taken to build them, which must have extended over years. No machines then existed for turning out accurately cut wheels in a few minutes or at most, hours. Every part had to

be made laboriously on the anvil and finished by hand, and the time taken to turn out a single wheel of perhaps sixty or eighty teeth must have been immense. It is a fact of no small historic interest that as far back at least as the days of Edward III. there were artificers capable not only of performing this work, but of conceiving designs which have persisted in all their essential particulars down to the present day.

Rack Type. Though universally used for turret clocks and for many small ones as well, the above type suffers from the drawback that if the striking and going trains get out of step, for example by one of them running down before the other, there is some trouble in putting matters right. The clock has to be made to strike all the hours round to the proper one. This can be done by raising the hind's foot by hand as often as may be necessary. Also, if it is necessary to set the hands, a pause must be made when the hands are at the hours or quarters as the case may be, to allow the hammer to strike its normal number of blows. Again, when once an hour has struck it cannot be repeated, and it is sometimes convenient to be able to do this at night when the hands cannot be seen. To overcome these disadvantages the rack or repeating mechanism was invented. Space does not permit of a detailed description, but it may be stated that it is the form generally used in common house striking clocks. Moreover, good descriptions of it are available in books such as Lord Grimthorpe's *Clocks and Watches and Bells*, and in the article "Clocks" in the *Encyclo-*

pedia Britannica. It must suffice to say that this striking mechanism may be allowed to run down or the hands may be set without reference to the striking mechanism, and without deranging the connexion between the going and striking trains. Also, on merely touching a lever the hour last struck may be repeated any number of times. It was invented by a Catholic Priest, Edward Barlow, who was born at Warrington in 1639. His real name was Booth, but he took the name of Barlow in honour of his godfather, Edward Barlow, a Benedictine monk known as Ambrose who suffered a martyr's death for his faith at Lancaster in 1641. Father Barlow was a distinguished horologist, and his rack striking mechanism which was first applied to clocks by Tompion in 1676, was not his only contribution to the art. He died in 1713.

CHAPTER IX

DRIVING MECHANISM

Weight-driven Clocks. The simple driving mechanism of the old clocks was subject to the defect that it ceased to drive while the clock was being wound up, for, in order to wind up the weight, the barrel evidently had to be turned in the direction opposite to that required for driving. In the absence of means for carrying on the work of the weights during the process, the clock would necessarily stop. Having regard to the magnitude of the weight and the considerable height through which it had to be raised, this operation took a time which might very well have run into hours. Though not generally provided against, this defect was met, in some cases at least, by a rudimentary form of a device of the kind called a " bolt-and-shutter " used in much later clocks. This consists essentially in a weighted lever temporarily applied to some part of the works while the clock is being wound. On the main wheel of the going train of the Wells clock there are four stout pins which have no obvious use in the mechanism, and it may have been that they were for the purpose of applying a lever. A more elaborate device with

the same object was fitted to the old clock of Exeter Cathedral, where it is still to be seen. It is the oldest example known, the date of the clock being 1317 at the latest.

The first generally adopted suggestion of means for meeting the difficulty was made by Huygens. His device, which is still to be seen in some 30-hour clocks, is shown fitted to the small clock in the right hand lower part of Fig. 13. Its principle can be best understood by reference to Fig. 17.[1] An endless cord passes over the driving drum or pulley *B*, and also over another pulley *C*,[2] the pivot of which is fixed to some part of the clock frame. The latter pulley carries on its edge ratchet teeth engaging with a pawl *D*, so that it can turn only in the direction of the curved arrow. The drum *B* is spiked or roughened so as to afford a grip for the driving cord. The cord hangs in two loops or bights, in one of which the driving weight *W* is suspended by a pulley, while in the other a lighter weight *w* is similarly suspended. While the clock is running down, the weight *W* is, of course, falling and the

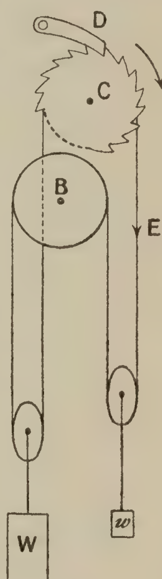


FIG. 17.
HUYGENS' MAINTAINING MECHANISM.

[1] This figure is in diagrammatic perspective. The pulleys from which the weights hang are at right angles to the plane of the paper. Hence their oval appearance.

[2] This pulley may be used to actuate striking mechanism.

weight w rising, the force which drives the clock being the difference of the two weights. During this time the pulley C does not rotate. In order to wind up the clock the cord is pulled at E in the direction shown by the arrow head. The wheel C can now rotate. The weight W is lifted and w lowered, but all the time the weight W continues to act on the pulley B in the proper direction for driving the clock.

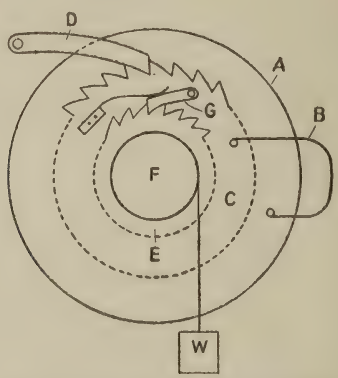


FIG. 18.—HARRISON'S MAINTAINING MECHANISM.

This mechanism was to a large extent superseded not very long after its invention by a device due to Harrison. It is shown diagrammatically in Fig. 18. The great wheel A, which is indicated by a plain circle, is carried loosely upon the common arbor of the mechanism and is connected by a spring B with a ratchet wheel C engaging with a pawl D, which is pivoted on the clock frame and permits rotation in one direction only—clockwise in the figure. The wheel C is also loose upon the

arbor. A second ratchet wheel *E* is fixed to the driving drum *F* and is engaged by a spring-pressed pawl *G* carried by the wheel *C*. The wheel *E* and drum *F* are both fixed on the common arbor. The teeth of the ratchet wheel *E* are directed oppositely to those of the wheel C. While the weight *W* is running down, the drum *F* and all the wheels turn clockwise, the wheels *C* and *E* rotating as one, on account of the pawl *G*, and the great wheel being driven by the wheel *C* through the spring *B*, which is compressed. While the weight is being wound up, the wheel *C* is held from rotation by the pawl *D*, but the great wheel continues to rotate in the same direction as before under the action of the spring *B*. During winding, the pawl *G* slips over the teeth of the wheel *E* and permits it and the drum to be rotated independently of the wheel *C* in the proper direction. A comparison with Plate II. will show that the present device differs only from the older one in the introduction of the wheel *C* and spring *B*.

Spring-driven Clocks and Watches. The idea of using a spring in the form of a long steel ribbon coiled into a spiral as driving means for clocks and watches appears to have first been put in practice by Peter Henlein, or Hele, of Nuremberg, about the year 1500. The device is too familiar to need much description, and it can be seen in action in most cheap clocks in which the springs are usually unenclosed. The outer end of the spring—the mainspring as it is called—is connected to the great wheel, and the inner end is hooked on to an arbor

controlled by a pawl and ratchet, so that it can only be turned in the direction for winding. In good clocks and watches the spring is enclosed in a drum or barrel which usually carries the great wheel on one of its faces.

It hardly needs pointing out that with this arrangement the spring continues to drive while it is being wound up, so that the difficulties experienced in this respect with weight-driven clocks do not arise. But spring-driven time-pieces have a trouble of their own, which is that the power of the spring

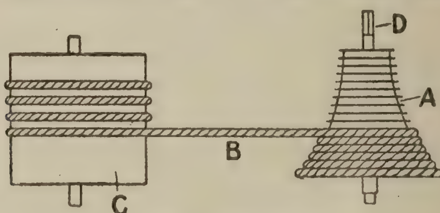


FIG. 19.—THE FUSEE.

diminishes as it unwinds, causing the rate of the clock to vary. More than one contrivance has been used to meet this difficulty, the most successful being the *fusee* invented by Jacob Zech about 1525. The device is shown diagrammatically in Fig. 19. The drum *A* performs exactly the same function as the driving drum of a weight-driven clock, but the cord *B*, which is wound round it, is pulled not by a weight but by a main-spring which is contained in the barrel *C*. The feature of the mechanism is the shape of the drum *A*. Its contour is approximately an hyperbola, and the effect is that as the cord unwinds from it, the force exerted by the cord acts at a progressively increasing leverage, thus making

up for the diminishing power of the spring, which, of course, is uncoiling itself at the same time. The fusee drum is grooved to keep the cord in its proper place, and the clock is wound by a key applied to the squared end *D* of the fusee arbor, thus winding the cord on to the drum and unwinding it from the barrel *C*. In the earliest fusees catgut cords were used, but afterwards chains were introduced by a Swiss clock-maker named Gruet in 1664.

Fusees are used in all marine chronometers and good spring-driven clocks. They were formerly universal also in watches, but they are very seldom, if ever, so used now. A watch goes better with a fusee than without one, but recent improvements in other parts of the mechanism have made the difference negligible. Moreover, the fusee is not readily adaptable to keyless mechanism. Also, it requires a maintaining mechanism to keep the timepiece going during winding.

Keyless Mechanism. Formerly all watches were wound by keys, and spring clocks and marine chronometers are still so wound, but a watch wound by key is now seldom seen. There are a great many varieties of keyless mechanism, but they all consist essentially of a double clutch rotated by the pendant knob which projects from the watch case. In one position of the clutch the knob is connected up to the winding gear and in the other to the hand-setting gear. The change over from the one position to the other is effected either by pressing on a spring button which projects through the edge of the case, or by pulling out or pressing in the knob.

CHAPTER X

WATCHES AND CHRONOMETERS

The Nuremberg Egg. Watches began their existence with the introduction of the main-spring, which invention, as has been stated, originated in Nuremberg. The earliest of them no doubt were merely portable clocks with square or drum-shaped cases, but from this it was a short step to make them suitable for wear on the person by smoothing off the corners, thus making them round or oval, from which circumstance and from their place of origin they were nicknamed Nuremberg eggs. They were originally worn as pendants, but the Puritans, to whom this practice savoured of sinful ostentation, took to carrying them in their pockets and so started the fashion which has prevailed to the present day.

The escapement and governing mechanism were of the verge and balance-bar types already described in connexion with the early weight-driven clocks, the adjustable hanging weights being replaced by knobs, which gave the balance somewhat the appearance of a dumb-bell. But a controlling device of this kind, however it might perform under the constant pull of a weight, is totally inadequate by

itself to control the varying force of a spring, and it is therefore hardly possible that spring-driven time-pieces in which the main-spring was entirely uncontrolled can ever have come into use. At any rate we do not hear of them. The absolute necessity for some additional mechanism to counteract the variation in power of the spring must have been evident at a very early date. The first mechanism designed for this purpose was called, for reasons which no one has been able to discover, a *stack-freed*. It consisted of a strong auxiliary spring which was strained when the time-piece was wound up, and which remained strained until the power of the main-spring began seriously to diminish. It then came into action and added its power to that of the main-spring. This device remained in use for the greater part of the sixteenth century, when it was gradually replaced by the fusee. But even with this improvement the Nuremberg egg must have been a sorry time-keeper. It is doubtful whether under favourable conditions it could be trusted to keep time within a quarter of an hour a day. What was wanted was something which, by controlling the balance, should make it act after the manner of a pendulum, but which should combine portability with isochronism. This requirement was met by the balance spring.

The Balance Spring. This device, which is more commonly called the *hair-spring* on account of its fineness, was the invention of Hooke. The effect of forces on elastic bodies was announced by Hooke in the aphorism, "ut tensio sic vis," meaning that

the deformation of a body is proportional to the force applied to it, or conversely that the force exerted by the body is proportional to its deformation. It can be shown without much difficulty to follow from this law that the oscillations of a freely vibrating spring are isochronous.

The application of springs to watch balances was suggested independently by others subsequent to Hooke, Huygens amongst them, but the priority must fall to Hooke. This and the anchor escapement give Hooke a foremost place in the history of

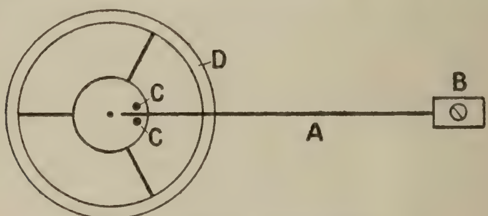


FIG. 20.—STRAIGHT BALANCE-SPRING.

clocks and watches, if not actually the first. No one else has to his credit two such important contributions to this class of machine.

The spring in its earliest application took the form of a straight strip *A*, Fig. 20, of some elastic material, usually steel, but a hog's bristle was sometimes used. It was fixed at one end *B*, while its other end passed between two small pins *C*, *C*, or some other restraining device on the arbor of the balance wheel *D*. The wheel and spring thus oscillated together, the rate of oscillation depending partly on the moment of inertia of the wheel, and partly on the stiffness of the spring. But much better results can be got by

disposing the spring in a spiral round the arbor of the balance wheel as shown in Fig. 21, which is taken from Huygens' *Opera Varia.* One end of the spring is attached to the arbor, while the other is attached to some fixed part *A* of the frame of the time-piece. The effective length of the spring and its consequent period of oscillation can be controlled with great nicety by causing its outer convolution to pass between two pins, called *curb pins*, carried by a lever which is pivoted coincidently with the axis of the balance wheel. The arrangement, which is not shown in Fig. 21, can be seen clearly in cheap spring clocks now in common use. By turning the

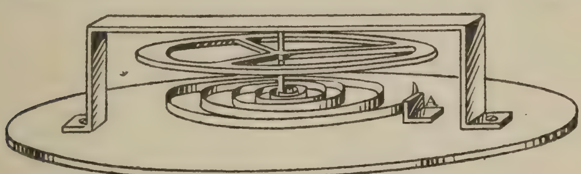


FIG. 21.—SPIRAL BALANCE-SPRING. (From Huygens' *Opera Varia.*)

lever in one direction or the other, more or less of the balance spring can be thrown out of action and its period of oscillation regulated.

The balance spring in the form illustrated, which is the form used in ordinary watches and clocks where great accuracy is not required, has the disadvantage of exerting unsymmetrical stresses upon the balance wheel arbor, with consequent uneven friction in the pivots. Many forms of hair-spring have been suggested to meet this trouble, but only two have come into general use. In one of these, called the *over-coil* spring, the spring is a flat spiral

for the most part, but its outer coil is bent out of the plane of the others and its end brought inwards over them to a point near the balance wheel arbor, where it is fixed to the casing. This form is also called the "Breguet" spring, after its inventor, a famous French horologist. In another form used by John Arnold, a London maker who lived in the latter half of the eighteenth century, the coils of the spring are disposed in a helix like a corkscrew, instead of in a flat spiral. Both ends can thus be attached to points on or near the axis of the balance wheel, and the coils are all of equal size. This form of spring is used in chronometers.

Watch and Chronometer Escapements. The verge escapement had a run of at least 600 years, for it was used in the earliest extant clocks, and watches fitted with it were made as late as the eighties of last century. With a hair-spring to help it, it must therefore have been capable of great efficiency. But it had the disadvantages that it was impossible to fit it into a thin movement; it was not dead-beat and therefore caused a recoil in the going train; there was excessive friction; and the balance wheel was never able to perform its oscillations freely in its natural period. To afford as far as possible a free swing to the balance is perhaps the main point to be kept in view in the design of an escapement. The less the swing is interfered with the closer the approximation to isochronism, and the best escapements are those which release the 'scape wheel and give the impulse to the balance as nearly as possible at the middle of the swing. If

these two actions are effected instantaneously, or almost so, while the balance swings freely for the rest of its movement, the escapement is called a *detached* escapement. All these remarks apply, of course, also to the pendulum. This requirement has best been met in watches by the lever escapement, and in chronometers by a special type, both of which we proceed to describe. These types have practically exterminated all others in the classes of timepiece to which they are severally applied.

The Detached Lever Escapement. This type is almost universally used in watches. It was invented about 1754 by Thomas Mudge, an apprentice to Graham and successor in his business. Mudge was a Devonshire man, the son of a clergyman, Zachariah Mudge, whose name entitles him to record. Mudge's lever escapement is shown in Fig. 22, the lower figure being an enlarged view of the parts adjacent to the balance wheel arbor. It consists merely in the application of Graham's dead-beat escapement to the spring balance. The anchor *A* has an arm *B* which terminates in two prongs *C*, *D*. These prongs are not in the same plane, and they are engaged alternately by cams or projections *E*, *F*, on the balance wheel arbor *G*. For distinctness the prong *C* and cam *E* in the plane of the paper are shown in full lines in the enlarged view, and the prong *D* and cam *F* below the plane of the paper by dotted lines. In the figure the tooth *J* of the 'scape wheel is sliding along the impulse face of the pallet *H*, and the balance wheel is receiving an impulse through the prong *C* and cam *E*, the balance rotating

as shown by the arrow. When this tooth has cleared the pallet *H*, the continued swing of the balance brings the cam *F* into action on the prong *D*, and puts the pallet *I* into position for receiving the tooth *K*. The swing of the balance then proceeds

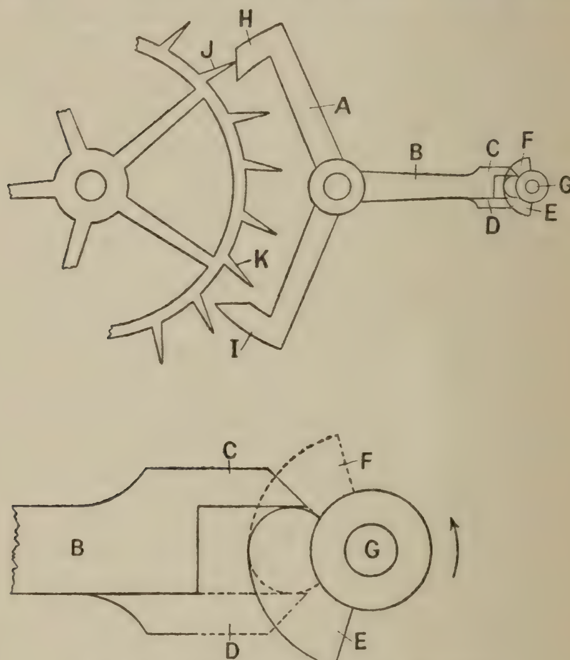


FIG. 22.—MUDGE'S DETACHED LEVER ESCAPEMENT.

without any interaction between the cams and the prongs. On the return swing the cam *E* encounters the prong *C*, the pallet *I* is released, and the tooth *K* slides along its impulse face, thus giving an impulse to the balance through the prong *D* and cam *F*; and so on. These actions are arranged to occur

almost instantaneously at the middle of the swing of the balance wheel. The balance wheel thus swings freely throughout the greater part of its motion. Means are provided for keeping the anchor in place while it is out of control of the cams, but these are not shown. It is somewhat remarkable in view of subsequent developments that Mudge thought very little of his invention. He only fitted it to two or three watches, and did not take the trouble to patent it.

Many modifications of this escapement are in use. The arm A, instead of being at right angles to the line of the anchor pallets, as in the figure, may be parallel to it, or inclined at any angle; or again, either the impulse or the dead faces, or both, may be formed upon the 'scape wheel teeth instead of upon the anchor pallets. These modifications, however, in no way affect the principle.

In cheap American clocks a form of lever escapement is used. If the reader examines one of these time-pieces he will see that the anchor pallets are represented by wire pins sticking out perpendicularly to the plane of the anchor. He will also notice that the teeth of the 'scape wheel are four sided, counting as a side the root where a tooth joins on to the rim of the wheel. He will see furthermore that the outside edge of each tooth slopes so as to form an impulse face. One of the other sides forms the dead face. This escapement gives most excellent results for its purpose. In fact, these clocks all through are models of good design, and for their purpose they are most efficient. With care they will last for years.

Nevertheless, it is surprising how many, if they stop, get thrown away in the belief that they are worn out, while all that may be wanted is a bath of petrol and a subsequent application of a few drops of oil. The writer has restored many to a life of usefulness in this way. The treatment may sound drastic, but it is after all less so than the old fashioned proceeding of boiling the grandfather's clock if it refused to go. Despite its grotesqueness the method of boiling a clock is a perfectly scientific way of cleaning it, and can do the clock no possible harm if care be taken to keep it warm for a few hours afterwards so as to dry it.

The Chronometer Escapement. An objection to the lever escapement is that it requires oil, small though the friction is between the anchor pallets and the 'scape wheel. The oil clogs in time, but it cannot be dispensed with when there are rubbing surfaces of substantial extent. In order to reduce these, and generally to realize as far as possible the requirements of an escapement, another form has been designed which is extremely efficient when applied to chronometers or other time-keepers not subject to much movement or to rough handling. Its delicacy, however, renders it unsuitable for ordinary watches. It is with but slight modification the design of Thomas Earnshaw, who invented it in 1784. A very similar device was invented about the same time by John Arnold, already mentioned in connexion with the helical hair-spring, and both were modifications of a French invention, but much improved.

In Fig. 23, which shows the principle of the chronometer escapement diagrammatically, *A* is the 'scape wheel and *B*, *C* pallets carried by the balance wheel arbor. *D* is a detent carried by a spring *E* attached to the framework. The detent carries a pallet *F*, the object of which is to lock the teeth of the 'scape wheel *A*, and it also carries a very light "passing" spring *G*, the end of which projects slightly beyond the nose *H* of the detent into the path of the pallet

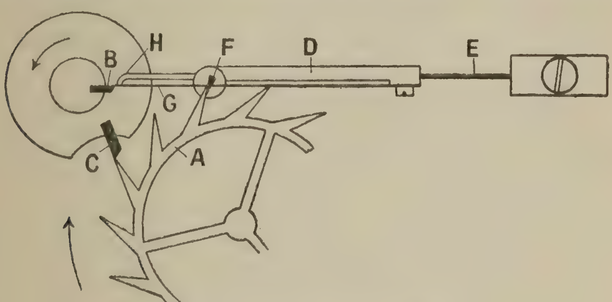


FIG. 23.—CHRONOMETER ESCAPEMENT.

B. When the balance wheel arbor turns counter-clockwise the pallet *B* catches the extreme end of the passing spring *G*, which is stiffened to receive the blow by the support of the nose *H* of the detent. The detent is thus raised, causing the pallet *F* to release a tooth of the 'scape wheel. In the figure this release is just about to take place. Almost simultaneously the pallet *C* receives a maintaining impulse from one of the other teeth of the 'scape wheel. After encountering the end of the spring *G* the pallet *B* passes to the upper side of it and the balance wheel continues its swing freely. On the return

swing the pallet *B* again encounters the spring *G* in passing from the upper to the lower side of it, but this time the spring *G* no longer has the support of the detent, and being very light is easily pushed aside. Hence the name *passing* spring. The strength of the spring *E* which carries the detent must be such as to return the locking pallet *F* after discharging a tooth of the 'scape wheel in time to catch the next tooth. The release and impulse are arranged to occur exactly in the middle of the swing of the balance wheel, which in practice amounts to rather more than one and a quarter turns.

Temperature Compensation. Spring balances, like pendulums, are influenced by changes of temperature, an increase of temperature causing reduction in the rate of the time-piece, and *vice versa.* But while this effect is brought about in a pendulum solely by alterations in its dimensions, the chief effect of heat on the spring balance is to alter the elasticity of the spring. The dimensions are, of course, altered as well, but this effect is not so important as the change in elasticity.

Three methods of compensation have been proposed: (1) the compensation curb; (2) the compensation balance wheel; and (3) the use of materials insensitive or irregularly sensitive to changes of temperature.

(1) *The compensation curb.* This method, though now obsolete, is of interest since it was used by Harrison in the chronometer which solved the problem of longitude, as will be related elsewhere. The reader will remember that the curb described

in the last chapter is a pivoted lever provided with pins embracing the outer coil of the balance spring, the effective length of which can thus be altered by turning the lever. In the compensation curb the movement of the curb pins is effected automatically by changes of temperature by means of a rod made of two strips of metal of different kinds, usually brass and steel, securely fastened together side by side. The effect of heat on this composite rod is to cause it to bend on account of the unequal expansion or contraction of the metals. One end of the rod is fixed, while the other carries the curb pins which, when the rod bends, alter the effective length of the spring, and therefore the time of oscillation, in the same way as the ordinary curb.

(2) *The compensation balance wheel.* It is found that interference with the length of the hair-spring involved in the use of the compensation curb affects its isochronism, and much better results are obtained by applying the compensation in the balance wheel itself. Fig. 24 shows the balance wheel of a chronometer. The rim of the wheel is made of two strips A and B of brass and steel fused together, the brass being outside and twice the thickness of the steel. The wheel has two spokes C. The rim is divided as shown close to each spoke, and each section carries a weight D which can be adjusted circumferentially on the rim. Two small screws E are provided for fine adjustment. Owing to the differential effects of heat on the two strips the sections of the rim open outwards or close inwards, carrying the weights with them, and to a

lesser extent the screws, thus changing the moment of inertia of the balance wheel as required. When the screws *E* and weights *D* have been adjusted so that the rate is as uniform as possible under variable temperature conditions, the period of swing is adjusted by nuts *F* placed exactly at the ends of the spokes. Since the spoke ends are the points of attachment of the rim, these nuts do not affect the temperature compensation. They affect the rate

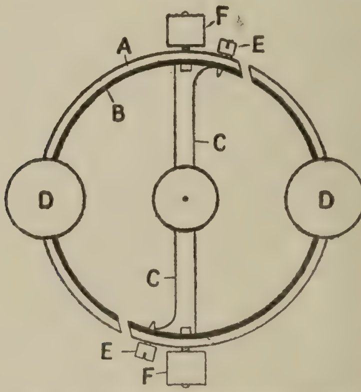


Fig. 24.—Chronometer Balance Wheel.

as a whole, while the irregularities of rate are eliminated as far as possible by the weights *D* and screws *E*. The balance wheel of a chronometer is about one and a quarter inches in diameter and, as stated above, its amplitude of oscillation is rather over one and a quarter rotations. Temperature compensated watch balances are made on exactly the same principle, but they are much smaller, and the sliding weights are replaced by a number of screws, similar to the screws *E*, distributed at

intervals round the circumference. Balances of this kind can be seen in almost any lever watch.

Balances made as above described are subject to the somewhat remarkable defect that they can be adjusted for uniform rate for two temperatures only. This, which is called the *middle temperature error*, means that in between or outside these two temperatures the going is irregular. This defect can be got over to some considerable extent by adding to the balance wheel auxiliary compensation devices constructed on the same bi-metallic principle, but it cannot be eliminated entirely.

(3) *Use of special materials.* Most metals and metallic alloys are very sensitive to changes in temperature. To a first approximation they expand fairly regularly. In the same metal rod equal rises in temperature produce nearly equal increases in length, but it is generally found that the increase tends to gain as the temperature rises. A brass rod, for instance, will lengthen more when raised from 20 to 30 degrees than when raised from 10 to 20. Several of the nickel-steel alloys, however, react to changes in temperature in abnormal ways. Invar, for instance, which has already been mentioned in connexion with pendulums, is one of them. It is almost insensitive to changes of temperature. Others, instead of expanding *more* proportionally as the temperature rises, expand less. In another alloy again, called *elinvar*, the elastic properties are almost unaffected, so that a spring made of this substance is unchanged in springiness whether it is warm or cool. It may therefore be readily imagined that

suitable combinations of these substances offer facilities for the construction of devices for the elimination of temperature errors. In fact, good authorities hope that one day an uncompensated invar balance wheel may be combined with an elinvar spring so that such errors as arise in each may be arranged to cancel one another, thus avoiding all the complications of auxiliary compensation which are now necessary for refined work.

Differences between Watches and Chronometers. The question is often asked, "What is the difference between a watch and a chronometer?" The question is not easy to answer if we take into account the past history of these time-pieces as well as their constructional features. No one, for instance, would refuse the name chronometer to Harrison's time-piece, already mentioned and to be mentioned again, which solved the problem of longitude, although it did not contain a single feature regarded as characteristic of the modern chronometer. Perhaps the most characteristic thing about a chronometer is the purpose to which it is applied. It is always used, or is always applicable, for the determination of longitude, more particularly at sea. But this is hardly an adequate definition, for watches are also used for the same purpose. We shall not go far wrong, however, if we adopt the following as a definition covering past as well as present time: *A chronometer is the most exact type of portable time-piece in use for the determination of longitude.* This might be truthfully said of any chronometer at any period of the history of the instrument.

But if we confine ourselves to the present time there is no difficulty about the matter. The works[1] of a chronometer differ from those of a watch, say, for example, a lever watch, in the following four points :

(1) A chronometer has a helical hair-spring, while the watch has a spiral one. If the watch is a very good one the spring will be of the over-coil or Breguet type.

(2) The balance wheel of a chronometer is regulated mainly by sliding weights ; that of a lever watch by screws. A chronometer balance almost invariably has auxiliary compensation for the middle temperature error.

(3) The chronometer escapement is of Earnshaw's type ; that of a lever watch is, as the name implies, a modification of Mudge's detached lever type.

(4) A fusee is always used in a chronometer, but has dropped out of use in watches in favour of the "going barrel." In the going barrel mechanism the main wheel is made in one with the barrel or drum which contains the main-spring, and forms one of the flat ends. The spring is wound up by turning the barrel arbor, upon which the barrel

[1] As this book is not intended for professional horologists no apology is offered for using the popular word "works" instead of the technical one "movement" for the going part of a clock or watch. The word recalls a story told (as far as the writer remembers) of Sydney Smith, cleric and wit. Sydney Smith and a Bishop (the writer forgets his diocese) set out to catch a train which, relying on the Bishop's watch, they missed. The Bishop expressed surprise and grief, saying that he had great faith in his watch. Smith remarked that it would be more to the purpose if he had works in it.

rides loosely, by a key or by keyless mechanism. Fusee mechanism is wound by the application of a key to the fusee arbor, on which the fusee is fixed. Though all spring-driven time-pieces, other than those controlled by a pendulum, go better with a fusee than without one, the advantage of simplicity gained by dispensing with it is held to outweigh the advantage of equalizing the power of the spring, when precise uniformity in time-keeping is not required. Moreover, the variations in power of the spring can be reduced, partly by using a long spring which is never wound or unwound to its full extent, and partly by the balance. Had an efficient balance, such as the hair-spring balance, been available when main-springs were first introduced, probably neither the fusee nor the stack-freed would have been invented.

To these four points of internal design we may add size and mounting. A chronometer is about the size of an ordinary American alarm clock, the dial being perhaps four inches across. It is usually mounted in a square box, on gimbals,[1] like a ship's compass, and for the same reason, namely, to allow it to remain horizontal however the ship rolls or pitches.

The term *chronometer-watch* is in use to designate a superior watch applied or applicable as a chronometer.

[1] This method of mounting consists in suspending the chronometer inside a ring concentric with it by pivots at opposite ends of a diameter. The ring itself is similarly suspended in the box by pivots, the line of which is at right angles to that of the former pair. However much the box may rock, the chronometer itself can remain at rest.

The Kew Certificate. There is much misconception about the standard of performance of watches. It is popularly supposed, for example, that a good watch should keep time within a minute a month. So it will if treated properly, but if it does, the fact is more a testimony to the regularity of the owner's habits than to the quality of the watch. An indifferent watch will keep respectable time if treated in the same manner day after day, but the best watch ever made will go erratically otherwise. If, for instance, it is wound at irregular intervals, if at night it is put sometimes face down and sometimes face up, or if it is put sometimes under the pillow where it is warm, and sometimes at the bed side, perhaps in frosty weather, a good performance cannot be expected of it, though, of course, it would behave better than a poor watch under such conditions. In order, therefore, that the reader may understand what sort of performance may be expected from a first-class watch, we propose in this section to give some account of the ordeal which it has to undergo in order to obtain a Kew Certificate, so called because the testing and rating of watches and chronometers used to be done at Kew Observatory. Though the work was transferred in 1912 to the National Physical Laboratory, Teddington, the certificates issued still continue to be called " Kew " Certificates.

To qualify for the " A " certificate, which is the best, a watch is tested for 45 days, the tests consisting in determinations of its *daily rate*, that is to say, its gain or loss per day. They are directed

mainly to ascertaining deviations from uniform rate, firstly when the temperature and position are unchanged, secondly when the position is changed, and thirdly when the temperature is changed.

The 45 days trial is divided into the following eight periods of five days each :

1.	Vertical, pendant	up,	at about	67° F.
2.	,, ,,	right,	,,	,,
3.	,, ,,	left,	,,	,,
4.	Horizontal, dial	up,	,,	40° F.
5.	,, ,,	,,	,,	67° F.
6.	,, ,,	,,	,,	92° F.
7.	,, ,,	down,	,,	67° F.
8.	Same as 1.			

An "intermediate day" is allowed at the commencement of each of the periods 4, 5, 6, and 7, when the temperature is changed, to allow the watch to adapt itself. Forty daily rates are observed in all, with five changes of position and two of temperature ranging over about 50° F. They embrace all the ordinary conditions of daily use.

The limits allowed are :

1. The mean variation of daily rate must not exceed 2 seconds in any one period.

2. The mean daily rate in any of the positional tests must not exceed 10 seconds.

3. The difference between pendant up and dial up must not exceed 5 seconds, and between pendant up and any other position 10 seconds.

4. The mean change of rate must not exceed 0·3 seconds for a change of 1° F.

It will be observed that condition (2) is the only one which does not refer to change of rate. The reasons for this concentration upon change of rate are fairly obvious. If a man knows that his watch gains 8 seconds a day and that it can be relied upon not to alter this rate materially, he can always make an allowance, and the result is to all intent the same as if the watch kept exact time. It will also be noticed that even a first quality watch might alter its rate by much more than a minute a month if it is not treated discreetly.

In carrying out these tests, five rooms are used. Three of these, in which the watches are kept, are maintained at the constant temperatures mentioned above. A fourth room contains a chronograph, and an apparatus which records the times received from Greenwich by telegraph, and from other places by wireless; both of these will be described presently. The room also contains various master clocks which control and distribute the time to the whole Laboratory. These last, however, have nothing to do with the present subject matter. The fifth room contains a six-valve wireless receiving set. The standard clock, by which the watches under trial and all the other clocks of the Laboratory are rated or set, as the case may be, is kept in the middle temperature testing-room.

This clock, which keeps Greenwich mean time, is enclosed in an air-tight case at a pressure of about 26 inches of mercury and is regulated by varying the pressure. The denser the air the greater its obstruction to the motion of the pendulum. An

idea of the nicety of this mode of regulation can be gathered from the fact that an increase or decrease of pressure of three inches would cause the clock to loose or gain about one second a day. The pendulum has an invar rod and a steel bob. Graham's dead-beat escapement is used. By means of an electric contact at the lower end of the pendulum a dot is made every second on the drum of the chronograph, which is shown in the front part of Plate VII.

This instrument, called a comparator chronograph, to give it its full name, is a type of time apparatus which we have not met with hitherto in this book. In one form or another it is used for comparing two time-pieces which are supposed to keep step, such, for instance, as two solar clocks, or the earth and a sidereal clock. But it is not applicable for comparing time-pieces which are not supposed to keep step with one another, such as a solar and sidereal clock. The method used in such a case will be explained in the chapter on Greenwich time. The indications of the comparator chronograph can be read to one-hundredth of a second.

The instrument at the National Physical Laboratory consists essentially of a drum 50 cms. long and 60 cms. in circumference, covered with a sheet of white paper. The drum is easily recognized in Plate VII. It is rotated by an electric motor through reduction gearing at a uniform speed of two rotations per minute. Two pointed tappers are mounted on a small carriage which is traversed lengthways of the drum and parallel to it by a lead-

Plate VII

[Reproduced by courtesy of Mr. A. Tremayne

CHRONOGRAPH ROOM, NATIONAL PHYSICAL LABORATORY

screw, after the manner of the slide-rest of a lathe, The carriage and lead-screw also appear clearly in the figure, the former being shown about half-way along the length of the drum. The tappers are actuated electrically, the one, which makes red dots on the paper, from the contact at the end of the pendulum of the standard clock, and the other, which makes black dots, by a tapping key operated by the observer who is testing the watches or chronometers in one of the adjoining rooms. The combined effect of the rotation of the drum and the traverse of the carriage is to produce a chart or record on the paper consisting of a spirally arranged series of red dots at 2 cms. intervals, representing the seconds of the standard clock, while interspersed between the red dots are black dots representing the moments of actuation of the observer's tapping key. The watch under trial is tested once a day. The reading of the watch is recorded by tapping the key when the second hand is at three positions symmetrically taken round its dial, and the mean of these is taken.

The certificate, which is signed by the Director of the National Physical Laboratory, states that the watch has passed the tests successfully, giving particulars of its performance and awarding a certain number of marks to it. The marks are based on the convention that a perfect watch would get 100 marks, and one, which just scraped through, no marks. A watch getting 80 marks or over is certified as "specially good." In 1919 a watch put the record in a safe place by getting 96·9 marks.

There is also a Kew Class "B" Certificate awarded after a trial of 31 days under less stringent conditions.

The trial of a marine chronometer extends over 55 days, divided into periods of 11 days each at mean temperatures respectively of about 70°, 45°, 70°, 95°, and 70°, in that order. All the temperatures are in the Fahrenheit scale, and the first day of each period is not counted. A chronometer qualifies for a certificate under these conditions: (1) that the mean of the differences in each stage of the trial between (*a*) the average daily rate during the period, and (*b*) the several daily rates, does not exceed 0·5 second in any one of the five stages; (2) that the changes of mean daily rate, caused by the alteration of temperature from period to period, do not exceed one-tenth of a second per 1° F.; and (3) that the mean daily rate does not exceed 7·5 seconds in any stage of the trial. Chronometers are tested only with the dial up, as they are always used in that position.

Admiralty chronometers for use in the Royal Navy are not rated at the National Physical Laboratory. This work is done at Greenwich Observatory.

In addition to ordinary watches and chronometers, the laboratory undertakes tests of stop-watches, such as are used for timing races.

The apparatus for recording the time obtained from outside for regulating the standard clock is shown at the back of Plate VII. The standard clock makes dots on a paper strip, shown hanging down beside the instrument, just as on the chrono-

graph sheet, and the signals received from Greenwich by wire through the Post Office, or from other sources such as the Eiffel Tower by wireless, are interspersed between the dots in the form of short or long strokes differing in length with the signals derived from different sources.

General Summary of the History of Clocks and Watches. In order to recall the reader's mind to the main points of the story related in the last few chapters, we give the following list of them with the names, where possible, of the inventors chiefly concerned, and the approximate dates. The names of the English kings reigning at the various times are added:

1348. (Edward III.) The Dover Castle clock.

1370. (Edward III.) De Vic's clock.

1392. (Richard II.) The Wells clock.

1500. (Henry VII.) Application of springs to clock driving by Peter Henlein or Hele of Nuremberg.

1525. (Henry VIII.) Invention of the fusee by Jacob Zech of Zurich.

1580. (Elizabeth.) Discovery of the isochronism of the pendulum by Galileo.

1639. (Charles I.) Publication of Galileo's researches on the pendulum.

1670 or thereabouts. (Charles II.) Invention of the hair-spring by Hooke.

1673. (Charles II.) Publication by Huygens of *Horologium Oscillatorium*, in which the application of the pendulum to clocks is described.

Date uncertain. (Charles II.) Invention of the anchor recoil escapement by Hooke.

1715. (George I.) Invention of the dead-beat anchor escapement by Graham.

1715. (George I.) Invention of the mercury compensation pendulum by Graham.

1726. (George I.) Invention of the gridiron compensation pendulum by Harrison.

1754. (George II.) Invention of the lever detached escapement by Mudge.

1759. (George II.) Harrison's chronometer.

1784. (George III.) Invention of the chronometer escapement by Earnshaw.

The above dates are approximate only. Most of them are variously given by different writers.

The Exeter Cathedral clock (1317, or earlier) is probably the oldest extant clock known. A clock in the Cathedral at Beauvais is said to be of a date prior to 1324.[1]

[1] An account of it is given in *L'Horloge de la Cathédrale de Beauvais*, by M. Paul Miclet (Beauvais, Imprimerie Départmentale de l'Oise). Accounts of the Ottery S. Mary and Exeter clocks appeared in the *Horological Journal*, vols. l. and lv., by Mr. J. J. Hall.

CHAPTER XI

ELECTRIC CLOCKS[1]

In the opinion of many competent authorities, electricity will eventually displace all purely mechanical methods of driving and regulating in the best class of clocks. The history of the application of electricity goes back some eighty years, and covers a wide field, including on the one hand the electrical control of clocks of ordinary mechanical construction, and on the other almost complete electrical actuation and regulation. We proceed to illustrate the progress which has been made by two examples, one very early and the other recent.

Fig. 25 is an example of a type of apparatus in which a master clock is used to regulate a number of others, all the clocks being otherwise of ordinary construction. The device was the invention of Mr. R. L. Jones, station-master at Chester, who took out a patent for it in 1857.[2] *A* is the pendulum of the master clock, *B* that of the clock to be synchronized

[1] The standard book on this part of the subject is *Electrical Horology*, by Langman and Ball (Crosby Lockwood and Son, London).

[2] No. 702, March 11, 1857.

with it. The bob of the pendulum *B* is a solenoid *N*,[1] and swings over two fixed permanent magnets *R*, *S*, which have similar poles opposed. The pendulum *B* has two suspension strips or springs, both of which do not appear in the figure since one is

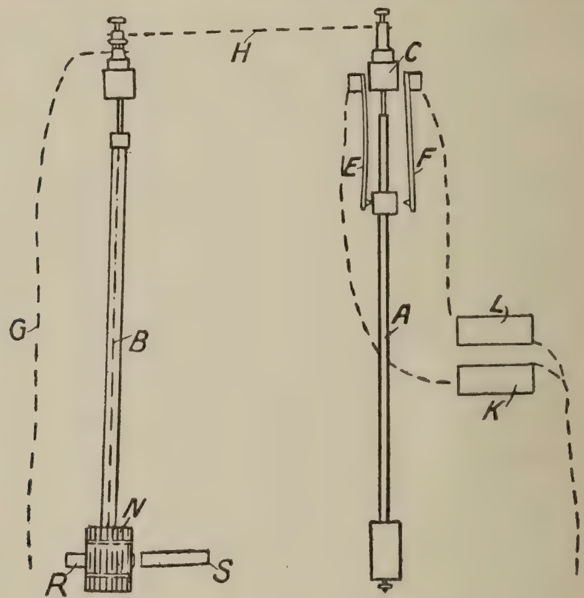


FIG. 25.—ELECTRIC CONTROL SYSTEM: R. L. JONES, 1857.

behind the other. These strips are insulated from one another. One end of the solenoid wire is con-

[1] A solenoid is a hollow coil of wire. When an electric current is passed through the wire the coil acquires the properties of a magnet, setting its axis north and south if it is free to turn, attracting iron, attracting or repelling the poles of other magnets, and so on. When the current ceases to flow, the solenoid loses its magnetic properties. Reversal of the current reverses the polarity of the solenoid.

nected to one of the strips, which is put to earth by a wire G, while the other end of the solenoid wire is connected to the other strip, and is thence connected by a wire *H* with the support *C* of the suspension strip of the master pendulum *A*. Near the top of the pendulum *A* is an enlargement which makes contact at each half-swing with light springs *E*, *F*. These are connected respectively to the terminals of two oppositely disposed batteries *K* and *L*, the other poles of which are earthed. The result is that at each swing of the pendulum *A*, the solenoid *N* is put in circuit with the batteries *K* and *L* alternately, its polarity being reversed each time. The interaction of the solenoid and the magnets *R*, *S*, forces the pendulum *B* to follow the oscillations of the pendulum *A* if it should tend to depart from synchronism with it. This system was in use for some time, but it has long been superseded. An obvious disadvantage is that if one of the controlled pendulums gets out of step by a whole beat with the master clock it can never recover. The normal times of oscillation of all the pendulums must be the same, as nearly as possible.

In the system just described every clock had to be complete in itself, with its own driving power, escapement and so on. The object was merely to get a number of ordinary clocks to go together. We shall now give an instance of a type in extensive use at the present time in which this complication is done away with. A single pendulum controls all the time indicators concerned, and the motive power is wholly electrical. The particular form we describe

is part of the subject matter of Patent No. 1945 of the year 1907.[1]

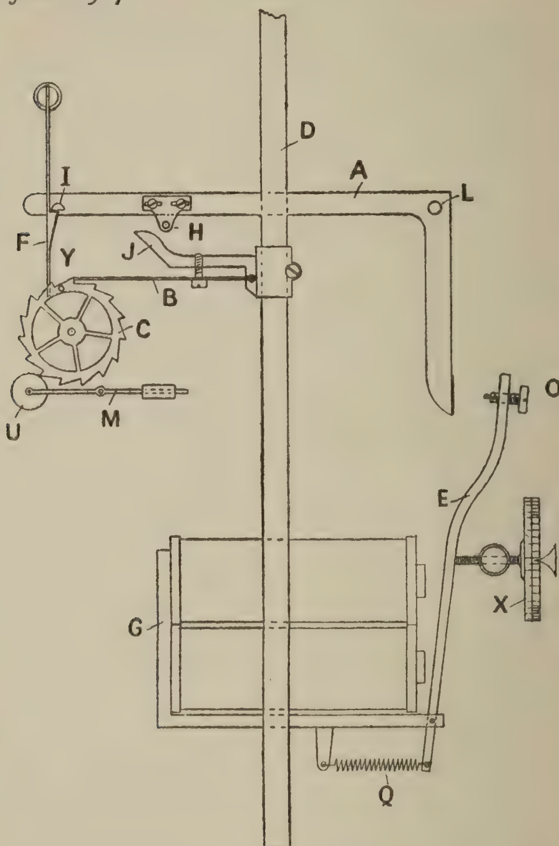


Fig. 26.—Electric Control and Driving System: Cunyngham and Hope-Jones, 1907.

Referring to Fig. 26, *D* is the pendulum rod, and *A* is a lever, called a *gravity arm* for a reason which

[1] Cunyngham and Hope-Jones are the patentees.

will presently appear, mounted on a fixed pivot at *L*. The longer arm of this lever carries a roller *H*, and also a pin *I* engaging with a spring detent *F* which holds this arm of the lever normally in a horizontal position. The shorter arm of the lever is vertical. The pendulum rod carries an arm *J*, the outer end of which is bent upwards at an angle as shown, and also a pivoted pusher *B* which turns a small wheel *C* tooth-by-tooth at each swing of the pendulum to the left. The wheel is prevented from running backwards by a roller detent *U* carried on a weighted lever *M*. At each rotation of the wheel *C*, a pin *Y*, which it carries, strikes the detent *F*, releasing the pin *I* and allowing the lever *A* to fall by its own weight. In so doing the roller *H* strikes the curved [1] sloping face of the arm *J* and imparts the impulse to the pendulum. This is arranged to happen exactly as the pendulum is in the middle of its swing to the left. The downward descent of the horizontal arm of the lever *A* is arrested by contact of the end of the vertical arm with a screwed stop *O* on the armature *E* of an electro-magnet *G*.[2] This

[1] The curvature of the acting face of the arm *J* is not a necessary feature of the apparatus. It is a refinement intended to make the action on the pendulum of the arm *A* uniform throughout its fall.

[2] An electro-magnet is a solenoid, the interior of which is occupied by a core of soft iron which is very often composed of a bundle of wires. The effect of the iron core is to concentrate the magnetic strength of the solenoid about the ends of the core. When the current ceases to flow the core loses its magnetic properties just as in the case of an uncored solenoid. If the core were of hard steel it would retain these properties. The *armature* of an electro-magnet is any adjacent piece of iron intended to be attracted by it.

armature is urged outwards away from the magnet by a spring *Q*, so that, excepting when the magnet is energized, it rests against a stop *X*, which is capable of very fine adjustment. The amount of descent of the long arm of the lever *A* and the consequent impulse given to the pendulum is thus always the same, and can be regulated with the greatest nicety.

When the shorter or vertical arm of the lever encounters the stop *O* it makes a contact which closes the circuit of the electro-magnet *G*. The armature *E* is then attracted, and in its movement to the left it throws the arm *A* upwards into its normal position, in which it is held by the engagement of the pin *I* with the detent *F*, ready for actuation when the pin *Y* comes round again. At the same time the contact at *O* is broken, the magnet is de-energized, and the armature falls back against the stop *X* under the influence of the spring *Q*. The usual period for these cycles of operation is half a minute, but of course, the mechanism may be designed for any period. The circuit of the electro-magnet may control any number of clocks or dials. The mechanism of these is extremely simple, the essential parts being an electro-magnet in circuit with the magnet *G*, having on its armature a finger which claws or pushes round a ratchet-wheel, just as the pusher *B* actuates the wheel *C*. This wheel drives the hands of the clock

It will readily be understood why the lever *A* is called a gravity arm and what are the main features of such a device. It is a rod which is lifted periodically always through the same height by some agency

other than the pendulum, upon which it falls, giving an impulse of the same amount each time. In the case just described the agency is electricity, but in the constant force escapements referred to in a former chapter the lifting of the arm is effected mechanically by the works of the clock. But the essential character of the device is the same in both cases.

CHAPTER XII

GREENWICH MEAN TIME

As stated in Chapter III, the mean solar day is the interval between two successive transits of the centre of the mean sun across the meridian on the same side of the pole, and Greenwich mean noon is the instant of this transit across the meridian of Greenwich on the south side. The mean sun is an imaginary body, and the instant of its transit must therefore be a matter of inference.

Amongst the duties of the Astronomer Royal, perhaps the chief one is to provide the public with a time scale. The zero of the Greenwich time scale is Greenwich mean noon, the length of the scale is the interval between two successive noons, and the graduations indicate the equal hour, minute, and second sub-intervals into which this main interval is divided. Time reckoned according to this scale is called *Greenwich Mean Time,* or shortly, *G.M.T.* The smallest sub-division on this scale is the second, though, of course, in arriving at it much smaller intervals come into account. But the scale as issued to the public takes no account of shorter intervals. The Observatory clocks, whether solar

or sidereal, all beat seconds, and no shorter intervals appear upon their faces.

It might be supposed that the simplest and most direct way of determining solar time would be to obtain true noon by observing solar transits and to apply the correction given by the equation of time. But this method is not susceptible of anything like the accuracy of stellar observations. Moreover, opportunities for observing solar transits occur but once a day, while in clear weather those for observing the stars are as many as the astronomer chooses to take, and the greater the number of observations the more accurate the result.

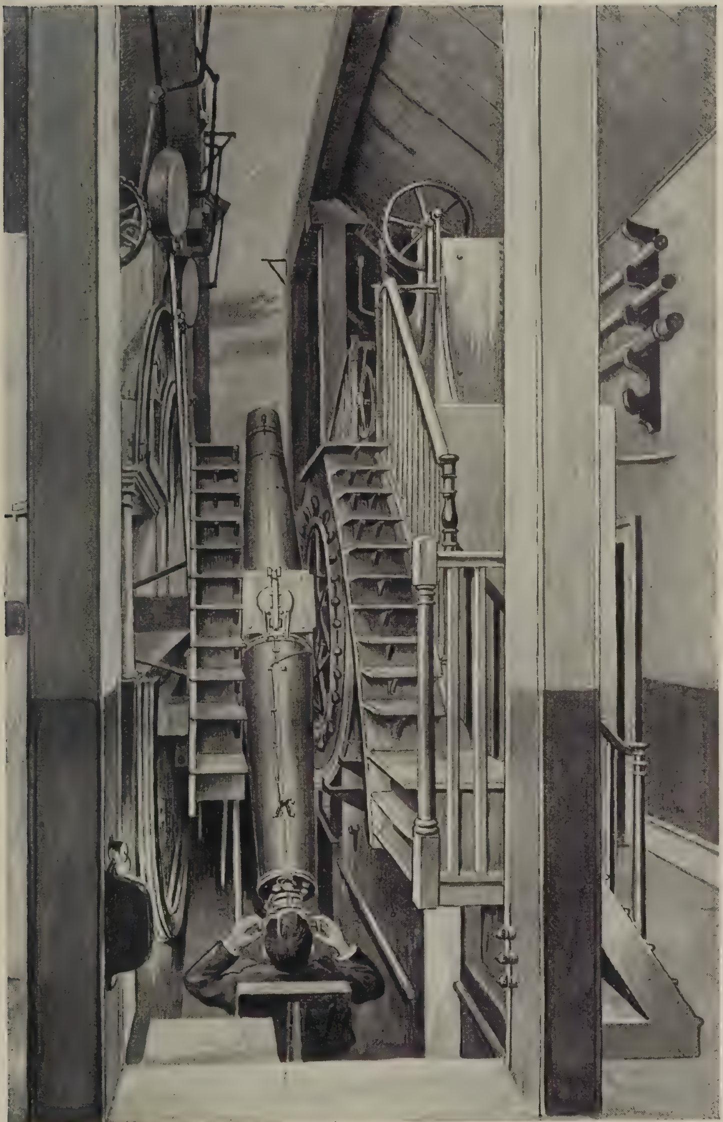
In the determination of time a series of operations is required, the object of which is to keep a clock, called the standard solar clock, going as nearly as possible exactly to mean solar time, and they fall into four divisions: (1) checking a clock, called the standard sidereal clock, which keeps sidereal time; (2) determining the error of the solar clock by comparing it with the sidereal clock; (3) setting the solar clock; and (4) broadcasting the time.

(1) *Checking the Sidereal Clock.* To perform the first set of these operations three instruments are used, the transit circle, the chronograph and the sidereal clock itself, and the whole business begins with the transit circle.

The transit circle, of which a picture is given in Plate VIII., is a telescope, eleven feet long, set up between massive stone piers so as to be capable of turning about an axis which points due east and west. Its optical axis, which may be described

roughly as the axis of the telescope tube, therefore, as will be understood from Chapter III, sweeps out the celestial meridian of Greenwich. It also marks the first, or zero, meridian of terrestrial longitude. Certainly the impressiveness of this instrument owes nothing to its surroundings, for it is installed in a small and most unimposing room in which there is scarcely space to move. And yet, this telescope is the most important landmark on earth of man's selection, since the others, the equator and the poles, are Nature's choice. There is no more enduring monument to the maritime greatness of the British race. It has been truly said that its story is the story of the naval and mercantile services of this country. British sailors selected Greenwich as the zero of longitude, and everyone else followed them as a matter of convenience. It is still retained and is unlikely to be changed, since no other place has any paramount claim. In like manner, Greenwich sets the time of the world, for the local standard time of every civilized country is always so many integral hours or half-hours after or before Greenwich.

This telescope carries a large graduated circle, from which the instrument gets its name—the transit circle. The circle is used for measuring the declinations of stars, but another object is to set the telescope to the known declination of the star which it is proposed to observe. The star will then drift into the field of view without further movement of the telescope. Fig. 27 represents the field of view of the telescope. In this field there is a vertical wire *A*, which can be moved across it by a screw actuated



[By courtesy of the *Illustrated London News*

TRANSIT CIRCLE, ROYAL OBSERVATORY, GREENWICH

by the observer as he is looking through the telescope, and as the wire reaches certain fixed points of the field an electric circuit is completed automatically, with an object which will shortly be made clear.

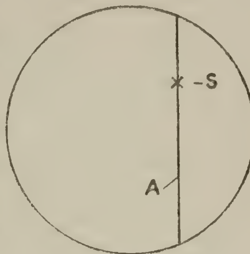


FIG. 27.
FIELD OF VIEW OF TRANSIT CIRCLE.

A list of some 200 or 250 "clock stars" selected for their convenience of observation is kept ready prepared. The positions of these are accurately known, more particularly their right ascensions which are, as will be remembered, the exact sidereal times of transit. When one of these stars, *S*, drifts into the field of view of the telescope the observer immediately covers its image with the movable wire, which he keeps steadily upon it by turning the screw as long as it remains visible. The star and the moving wire thus traverse the field together. The electric circuit is closed each time the wire crosses the fixed points, and the event is registered by the chronograph.

The chronograph is similar in principle to the one used at the National Physical Laboratory for rating watches and chronometers. In consists of a cylindrical drum, about two feet long by a foot in diameter, which is rotated at an approximately uniform rate by clockwork. The drum is covered with a sheet of white paper, upon which rests a pen. The pen traces a continuous spiral on the paper except when the circuit at the transit

instrument is closed. The holder which carries the pen is mounted on the armature of an electro-magnet, the coil of which is in circuit with the switch on the transit circle, so that every time the observer, following the motion of the star at the telescope with his moving wire, automatically completes the circuit, a triangular dent is made in the spiral. Precautions are taken for distinguishing the dents corresponding to the wire in different parts of the field, so that no confusion shall arise in reading the record.

We now come to the sidereal clock and its functions. In spite of its exalted position as the chief clock of the world, there is nothing in outward appearance to distinguish it from any other clock, excepting that it is sealed up in an air-tight glass case to prevent changes in barometric pressure from altering the density of the air immediately surrounding it and so affecting its rate. It is of English make but with an escapement devised in Germany.[1] The pendulum rod is made of invar, and there is no temperature compensation. The clock occupies, with seven or eight others, all looking very much like ordinary grandfather's clocks, amongst them being the solar clock, a small room, or rather closet, with double doors to enable it to be kept at a fairly constant temperature of about 60° F. Its rate of going is wonderfully uniform, and it is never set or meddled with in any way. All that is done is to determine its error from true sidereal time by the

[1] The Riefler escapement. The details are too technical for this book. See *Encyclopedia Britannica*, article " Clocks."

operations now being described. A good clock of this sort ought not to change its rate by as much as 0·03 seconds a day.

The sole office of the sidereal clock is to complete an electric circuit every second, corresponding to the oscillations of the pendulum. When the circuit is closed a dent is made in the chronograph record similar to those made by the transit circle but smaller. These dents are about an inch apart.

It will now be clear that, having the transit marks and the sidereal clock seconds marks on the same chronograph record, the data are supplied for telling the time of transit *according to the clock*. Comparing this time with the known right ascension, which is the true time of transit, we get the error of the sidereal clock. A number of stars are observed and the chronograph gives several records of the transit of each, corresponding to the known positions with reference to the meridian of the points in the field of the telescope at which the electric contacts are made. The data obtainable in clear weather are thus both numerous and accurate. Indeed, it occasionally happens that comparison of a number of observations leads to the detection of some previously unperceived error in the position of one of the clock stars. Furthermore, by comparison of the results of observations taken night after night the rate of the clock, that is how fast it is gaining or losing, and any changes in its rate are determined.

The above-described method of observing transits by covering the star with a moving wire is a German idea of comparatively recent introduction. Formerly

the observer watched the star moving across fixed vertical wires while he listened to the ticking of the standard clock which stood beside him. When, as was usually the case, the crossing of a wire by the star took place in the interval between two ticks, the observer had to subdivide this second of time mentally and estimate at what fraction of a second the crossing actually occurred. It is said that a skilled observer could estimate this instant to a tenth of a second, but it sounds like a miracle of skill. The next step was the introduction of the chronograph with an electric circuit, this circuit being completed by the observer himself, who pressed a button when he thought the star was on one of the wires. This, of course, was a great simplification, since the chronograph, as it does now, subdivided the seconds for the observer and relieved him of the necessity of doing it in his head as before. But there were two sources of error which were not eliminated. Firstly, an error due to differences in the brightness of stars, and secondly the error called the personal equation. If a star is bright it is always thought to come into coïncidence with a wire earlier than if it were faint. The moving wire completely eliminates this source of error. Again, a sensation received at the surface of the body takes some time to reach the brain and thence to be translated into action. Hence, even if the transit is correctly judged, an appreciable time may elapse before pressure is applied to the button. The observation is therefore usually recorded a little late. It may on the other hand happen that an observer in his

anxiety to be in time actually records the transit before its occurrence. The errors arising from these two last sources are collectively called the *personal equation*. The personal equation differs for different people, but it is approximately the same for the same person, saving for irregularities due to the state of his health or other accidental causes. Everyone's personal equation can be determined by experiment and allowed for, and this was the course adopted until the introduction of the present method. This method reduces the personal equation to one-tenth of its former value, which, as it was small to begin with, means its practical extinction.

For clearness let us re-state the objects of the transit observations. They are to determine (1) the actual error at a given time of the standard sidereal clock, and (2) the rate of the clock, that is to say how fast the clock is gaining or losing time on the stars. With these two data the error of the sidereal clock at any subsequent time can be determined, assuming the rate to be constant during the interval. The frequency of the observations and the excellence of the clock insure the fulfilment of this last condition.

(2) *Checking the Solar Clock.* For this purpose the sidereal and solar clocks have to be compared, an operation which is perhaps the most interesting of the series but which is by no means easy either to explain or to understand. Nor is it a simple matter to carry out, the complication arising chiefly from the fact that the movements to be compared are not continuous but step by step,

and are at the same time not *in* step with one another.

For various reasons it is inconvenient to make the comparison directly between the two main clocks. It takes place in a room specially allotted to the purpose on a piece of furniture called the *time desk*, upon which are two small auxiliary clocks and a ledger in which the records are kept. The auxiliary clocks are placed side by side and are controlled electrically by the main sidereal and solar clocks respectively, the indications of which they repeat exactly and instantaneously. They thus both beat seconds, the one sidereal, and the other mean solar, giving out at each beat a loud and distinctive tick. The movements of the hands of these desk clocks are not continuous, but intermittent. The seconds hands like those of the main clocks read to whole seconds only, and move from one division of the dial to the next by a jump which takes place at each tick. For the most part the ticks of the two clocks do not occur together, but they coincide at certain intervals. These coincidences occur every 6 minutes 5 seconds mean solar time, for since 366 sidereal days are equivalent to 365 solar days, and these days are similarly divided into hours, minutes, and seconds, 366 sidereal seconds must be equivalent to 365 mean solar seconds, which is to say that at every 6 minutes 5 seconds solar time the clocks tick together. The precise method of making the comparison requires to be witnessed to be understood properly. It must suffice to say that the absolute times, whether sidereal

or solar, when the coincidences *should* occur can be computed beforehand, and the reading of either clock when they actually *do* occur is an indication of the amount of the error. The process is very like reading a vernier on a length or angle scale. It is, in fact, called the vernier method of comparison.

To listen to the tickings and watch for the coincidences is an interesting experience. After a coincidence the tickings, which are readily distinguishable on account of the difference of their sound, are heard to separate slowly and almost imperceptibly until they are half a second apart. Then they approach just as gradually until a coincidence again occurs 365 solar seconds after the last. To the uneducated ear a coincidence is by no means as easy to recognize as it might seem. The sound of a tick appears to affect the auditory organs as a flash of light affects the visual ones, and the impression seems to persist for a time. At least the writer hopes that there is some such explanation of his own deplorable failure to distinguish between the ticks when they were separated by no less an interval than a tenth of a second. So at all events he was informed, and it is not for him to dispute it.

(3) *Setting the Solar Clock.* The solar clock is, of course, a very good one, as clocks go, but, seeing that it is set right at frequent intervals, it is not necessary for it to be so good as to be trusted to keep its rate for days together when celestial observations are not possible. Its pendulum rod is steel surrounded for part of the length by a zinc tube,

the differential expansion of the two metals giving the temperature compensation. About the middle of the rod is attached a permanent horse-shoe magnet. The poles of the magnet at each oscillation pass over and close to the poles of electro-magnets, the coils of which are in circuit with a switch on the time desk mentioned in the last section. The switch is a double one, so that the current through the coils of the electro-magnet retards or accelerates the pendulum according to the position in which the switch is held. The strengths of the horse-shoe magnet and of the current are so adjusted that closing the switch for one minute advances or retards the clock by one-tenth of a second. Thus, to put the clock forward or back by ·15 of a second the switch must be held closed for 1½ minutes. In order, therefore, for the operator to apply the correction determined in the manner described in the last two sections, all he has to do is to hold the switch over in one position or the other for a length of time equal to one minute for every ·1 seconds error.

(4) *Distributing the Time.* On the 'scape wheel arbor of the solar clock,which rotates once a minute, is a small wheel with sixty teeth. Once a second a tooth completes an electric circuit which controls clocks in different parts of the Observatory, amongst them the solar desk clock, and the large twenty-four hour clock in the wall just outside the main gateway so familiar to the public. Something went wrong with this clock once, a piece of misbehaviour instantly seized upon by a well-known watchmaking

company, who forthwith issued an advertisement, " Greenwich time proved one minute fifteen seconds wrong by a —— watch," to the great entertainment of all concerned.

Greenwich mean time is sent to the General Post Office every hour. The electric circuit for doing this has two switches in series, that is to say both must be closed at the same time for a current to pass. The switches are mounted on the framework of the solar clock. One of them is closed every hour by a pin moving with the minute hand about half a minute before the exact hour, and opened about half a minute after. The other is closed and opened at every exact minute, the duration of contact being almost instantaneous. Nothing results from 59 out of 60 of these last contacts, for the hour switch is open, but at the 60th contact the current passes since the hour switch is closed. The reader will not fail to notice the analogy between this device and the striking gear of the clock described in a former chapter. The closing of the hour switch corresponds to the preparation or warning. A contrivance of this kind is often required in cases where a slowly moving part—in the present instances a pin moving with the hour hand—is concerned in the performance of some instantaneous act.

At one o'clock every afternoon a ball is dropped from the top of a mast erected on the top of one of the Observatory buildings. Shortly before one o'clock it is raised by a hand winch and is held up by a catch which is released by an electro-magnet in the circuit, which gives the hour signal

to the Post Office, or in a shunt from it. The ball is five feet in diameter, and it occurred to some ingenious person at the Observatory to make it represent the sun in a model of a sun-earth-moon system. Accordingly, there has been set up on a convenient roof some 200 yards off a lath about 18 inches long with a small ball at each end to represent the earth and the moon, about a half and an eighth of an inch in diameter respectively. These are sizes to scale, and the Observatory astronomers invite the visitor to notice how the " sun " can be obscured by the " moon " when the eye is at about the distance of the " earth " from the " moon," so as to give him an idea of what is happening at a solar eclipse.

Beyond the 24-hour clock in the wall, the time ball and the hourly signals to the Post Office, the Observatory does nothing towards publishing the time. This is the business of the Post Office. The only public clock in direct communication with Greenwich is the " Big Ben " clock of the Houses of Parliament. Twice every day this clock reports itself automatically to the Observatory by electricity, and the reports are entered in the time book. The clock seems to be an astonishingly good one. The entries which the writer inspected showed it to be right with the Greenwich solar clock within two or three tenths of a second. Of course, it would be unreasonable to expect such an accuracy consistently from a public clock. But, according to the report of the Astronomer Royal for 1922-23, its observed error exceeded three seconds on three occasions only. The clock is not regulated from Greenwich,

but if an error tending to become serious is noticed, Messrs. Dent, who look after the clock, are informed.

Harrison's Chronometer. Amongst the treasured possessions of Greenwich Observatory is the chronometer which solved the problem of longitude at sea. It has the appearance of an old-fashioned silver-cased watch, pendant and all complete, but it is much larger—about five inches in diameter. It is still in going order. Not one of its features survive in the modern chronometer, but it proved the feasibility of using a time-piece for the determination of longitude. The followers of a pioneer do not always use his path, but there would have been no path at all but for him.

As may be gathered from the section on local time in Chapter III, the determination of longitude is a matter of the simultaneous comparisons of the local times of two places, and it is evident that in order to make this comparison there must be some means for acquainting an observer at one place with the local time at the other. The difficulty was to provide these means. The problem was extremely pressing, for, after the discovery of America in 1492, navigation out of sight of land became the rule and not the exception.

The determination of latitude gave little trouble, but longitude involved one of the stiffest problems ever set to mankind, a problem which withstood the efforts of the cleverest brains in the world for more than 250 years from the days of Columbus. Various purely astronomical methods were tried with little success, and the obvious alternative of

a time-piece which would give Greenwich time to the seaman, and thus enable him to compare it with his local time, was not available, for no clock had yet been made, nor as it then seemed could be made, which would go uniformly for the duration of a voyage.

Large rewards were offered for the solution of the problem; amongst them one of £20,000 by the British Government for a method which would enable a ship to make a voyage from a British port to the West Indies and back without erring in its longitude by more than half a degree, and smaller sums were offered for the fulfilment of somewhat less stringent conditions. The major reward was won by Harrison with his chronometer. He may be said to have devoted his life to the one object of solving the problem, and this was his fourth effort. It was completed in 1759 and made the round voyage to the West Indies and back in 1761 and again in 1764, complying with the conditions each time. But even so, the authorities were unwilling to admit that his success was anything more than a happy accident, and it was only through the personal influence of King George III. that the reward was eventually paid in full.[1]

[1] The history of longitude is very lengthy. For further particulars the reader is referred to *The Marine Chronometer* by Lt.-Commander R. T. Gould (London, J. D. Potter) and to the *Royal Observatory Greenwich, its History and Work*, by E. W. Maunder (London, R. T. S.). Most unfortunately this latter book is out of print.

The clearest and most concise account with which the writer is acquainted of ways of determining latitude and longitude, including methods of determining local time at sea, is to be found in *Lloyd's Calendar*, an annual publication issued by Lloyd's for the use of seamen.

CHAPTER XIII

THE CALENDAR

THE subject of the calendar is a very large one. Every civilized nation from remote antiquity has had a system peculiar to itself, and there is more than one in use at the present time. We shall confine ourselves to the main facts concerning the Gregorian Calendar, which is the one almost universally used. The Mahometan world, and for religious purposes the Jews, have calendars of their own.

The divisions of time which figure in all calendars are the day, the week, the month and the year. Of these four, the day, the month, and the year are what may be called natural measures, since they are based upon the succession of day and night, the phases of the moon, or the annual motion of the sun. The week is not a natural division of time. It is an artificial period of seven days which has come down to us from remote times, and its origin is obscure. It may have been chosen on account of its approximate relationship to the phases of the moon, while some think that the seven days correspond to the seven planets known to the ancients,

the sun and the moon being counted as planets. The names of the days of the week give some colour to this latter supposition. But whatever its origin, of all the four periods the week has given the least trouble to calendar makers, for the reason that it contains an exact number of days.

What has really caused the trouble is the fact that none of the other three periods have any exact mutual numerical relationship, and the whole story of the calendar is the story of attempts to fit together these three incommensurables. It would have been easy, and it was in fact done, to lay down rules to the effect that the month should contain some integral number of days, and the year so many integral months or days, but the periods so computed continually got out of step with the phenomena upon which they were supposed to be based, and endless confusion arose. If, for example, it was laid down, as it was by the ancient Egyptians, that the year should contain exactly 365 days, it is clear that the seasons lost time at the rate of a day every four years. But the difficulty of squaring the day with the year was as nothing compared with the trouble the moon gave, and yet it was not until the time of Julius Caesar that for civil purposes the moon was left out of account and the efforts of calendar makers concentrated upon the day and the year. This reluctance to abandon the moon as a time measurer is intelligible enough. Its phases are as striking as any phenomena which the heavens present, and might seem almost specially designed for the purpose. For ecclesiastical purposes its influence still survives in

the complicated rules for finding Easter, which remains a movable feast.

The Julian Calendar. Our present calendar dates back to the Romans and was based during the early part of its history on an almost purely lunar reckoning, the lunar month being sometimes taken as 29 and sometimes as 30 days as approximations to the interval of a lunation, that is to say the interval from new moon to new moon,[1] which is about 29½ days. Tradition says that Romulus adopted a ten month year of 304 days, but exactly how this was divided into months or how the remaining days of the year were accounted for is not very clear. At any rate the ten month year still survives in the names of our months from September to December inclusive. The year began in March, and July and August were called Quintilis and Sextilis respectively. Numa, who reigned at Rome about 700 B.C., added two months, January at the beginning and February at the end of the year, but this order was changed to its present one in 452 B.C. The months consisted of 29 and 30 days alternately, making 354 in all, but because of the dislike of the Romans to even numbers, which they supposed to be of evil omen, one day was added—" one for luck " as we say. This made 355 days, which was more than ten days short. Accordingly, a somewhat complicated practice was resorted to of putting in an extra or intercalary month, sometimes of 22 and sometimes of 23 days, between the 23rd and 24th of February. The effect of this was to bring the

[1] Or, of course, the period of recurrence of any phase.

average length of the year to 365¼ days. This made the year about its proper length, but unfortunately these intercalations were left largely to the discretion of authorities who did not scruple to use them for corrupt purposes. If it were desired to prolong or curtail the term of office of a magistrate or to arrange for an election at some time convenient for themselves, there was always a balance of days for these authorities to draw upon. In order to put an end to such like abuses, Julius Caesar, with the help of the Greek astronomer Sosigenes, altered the calendar completely into what is very much like its present form. Amongst other things he made the year commence on January 1, and arranged so that the vernal equinox should fall on March 25th, as it did in the time of Numa. But his great reform was to throw over the lunar month completely. The months, commencing with January, were to consist alternately of 31 and 30 days, excepting February which had 29 days, or 30 every fourth year. This divided the years into cycles of four, three consisting of 365 days and one of 366, and thus arose what we call *Leap Year*. He also renamed the month Quintilis after himself, whence our word July. These reforms came into effect on January 1, 45 B.C., which was the day of the first new moon after the winter solstice. In order, however, that the year should commence on this date he had to make the previous one contain 445 days, and it is not surprising that this latter year came to be known as the "Year of Confusion."

Julius Caesar did not live long enough to see this really great and valuable reform carried out completely, and it was impeded for a time by a curious mistake. Instead of intercalating a day in February every fourth year as Julius intended, it was by a misunderstanding of his enactment added every third year. This, however, was corrected by his successor Augustus in 8 B.C.. But Augustus spoilt to some extent the work of Julius by a piece of petty vanity. Not to be outdone by Julius he wanted a month to himself, and accordingly he appropriated Sextilis, to which he gave his own name, whence our August. Unfortunately, Sextilis had the inferior number of 30 days, which was not to be borne. He therefore deprived February of a day and added it to August, and altered the succeeding months, which allotment survives to the present time.

The Gregorian Calendar. The Julian Calendar, as it came to be called, served the world well for upwards of fifteen centuries, but it had the defect that it made the average length of the year exactly $365\frac{1}{4}$ days, which is slightly longer than the tropical year, with the result that the vernal equinox recurred at progressively earlier dates. At the time of the Council of Nicaea, in 325 A.D., it had receded to March 21, but though, as we shall presently see, this council concerned itself with the Church Calendar, it did not meddle with the civil one, and nothing was done at the time. But by the end of the sixteenth century the vernal equinox had gone back ten days more to March 11, and Pope Gregory XIII undertook reforms of the calendars, both civil and

ecclesiastical. In this he was helped by two astronomers, Clavius, a Jesuit, and Luigi Lilio Ghiraldi, a Neapolitan physician whose name has been Latinized into Aloysius Lilius. We are not concerned with the ecclesiastical calendar at present, but the immediate effect on the civil calendar was to restore the vernal equinox to March 21, the date on which it fell at the time of the Council of Nicaea. In order to keep it at that date Gregory dropped the extra day in February every century year except in those years whose numbers are divisible by 400. Thus, 1600 was a leap year because 1600 is divisible by 400, but 1700, 1800, and 1900 were not. The year 2000 will be a leap year. This modification of the Julian rule that there should be a leap year *every* fourth year constitutes what we call the *Gregorian Calendar*, or the *New Style*. This is at present in use in all civilized countries. Russia adhered to the Julian or *Old Style* until about the end of 1917, when the New Style was adopted.

Pope Gregory did his work well. In every cycle of 400 years there are, according to the Gregorian rule, 97 leap years of 366 days and 303 common years of 365, making 146,097 days in all. Reckoning 365 days, 5 h. 48 m. 46 s. to the tropical year, there are in 400 such years 146,096 days 21 h. 6 m. 40 s. a difference of less than three hours. Gregory's average year is thus a little too long, but it takes over 3300 years for the vernal equinox to go back by a single day.

The Gregorian Calendar was adopted under a Papal bull in the Catholic countries in 1582, but the

times were unpropitious for the adoption in Protestant countries of anything emanating from such a source, however useful and even necessary it might be. The record of Pope Gregory in particular was singularly unfortunate from this point of view. The Massacre of St. Bartholomew had occurred about ten years previously, and whether, as his apologists say, through misinformation as to the designs and characters of the Huguenots, or otherwise, he was ill-advised enough to hold public rejoicings in Rome on the occasion. Moreover, trouble was being raised in Ireland against Elizabeth, which he got credit for fomenting, and he was undoubtedly backing Philip II. in his designs against this country and the Netherlands. And this was not all, for the incident of the Spanish Armada was still to come. The result was that the adoption of the Gregorian Calendar in non-Catholic countries was delayed to a much later date. It was not put in practice in this country until 1752, by which time the vernal equinox had gone back another day since the time of Gregory. In that year, therefore, 11 days had to be dropped. There was much opposition in consequence, people thinking that their lives had been shortened. The cry arose, "Give us back our fortnight," and riots broke out in many places, especially in Bristol where several people were killed. It is to be feared that we cannot laugh at these unhappy people: have we not our own objectors to summer and winter time?

The Ecclesiastical Calendar. Solar, Lunar, Dionysian and Julian Cycles. We have no intention of going into detail into the mode of determining the movable

feasts of the Western Church, with its terrible array of Dominical Letters, Golden Numbers, Epacts and so forth. We prefer to exercise the prudent restraint of the writer of the article on Easter in Chambers' Encyclopedia and say with him that it is too complex for description here, contenting ourselves with a few broad facts.

All these feasts depend upon Easter, about the date of which there was division in the Church at the beginning of the fourth century A.D., some adhering to the practice of celebrating Easter on the Jewish Passover, while the more general feeling seemed to be that it should always be celebrated on a Sunday. This, and a number of other matters concerning the faith, were referred by the Emperor Constantine to a great council of more than 300 delegates which assembled in the year 325 at Nicaea in Bithynia. The Council of Nicaea, desiring as far as possible to avoid Judaising influences in the Church, decided for the Sunday observance of Easter, and the rule they framed was specially designed so that Easter should not coincide with the Passover, which feast is held on the first full moon of spring, that is to say, the full moon immediately following the day of the vernal equinox, or on the day of the equinox if it should happen so to fall. The rule which the Council laid down is that *Easter day is the Sunday immediately following the full moon which falls on or next after the vernal equinox* ; *but if this full moon falls on a Sunday, Easter day shall be the Sunday following.* For the purposes of this rule the fourteenth day of the moon is reckoned as the full moon. The rule,

simple though it looks, is not so easy to carry out, for reasons which cannot be given without a lengthy discussion.[1] We may, however, observe that the selection of a particular day of the week brings in yet another complication besides the month and the year.

We shall not pursue the subject of Easter further, but we may observe that in carrying out the Easter rule, use is made of certain cycles which call for some notice, as they possess an interest outside ecclesiastical matters. These are the Solar Cycle, the Lunar Cycle, and the Cycle of Indictions.

The Solar Cycle is a period of 28 years, after which the days of the month fall upon the same days of the week. Of course this does not mean that there are not shorter periods within this cycle in which the same thing happens, but these periods are of unequal length, while the periods of 28 years composing the Solar Cycle are the shortest which are *all* of the same length. The reader can easily verify this for himself.

The Lunar Cycle, also called the Metonic Cycle, after the Greek astronomer Meton who discovered it about 430 B.C., consists of 19 solar years, which comprise almost exactly 235 lunations within a couple of hours or so. After every 19 years, therefore, the new moons recur on the same day of the month. The product of these two periods, 19×28 or 532 years, is called the Dionysian Cycle, after

[1] The matter is gone into in considerable detail in the article on the Calendar in the *Encyclopedia Britannica*; also, as everyone knows, in the *Book of Common Prayer*.

Dionysius Exiguus, or Denys the Little, a monk and ecclesiastical writer who lived in Rome in the first half of the sixth century. It obviously combines the properties of the Solar and Lunar Cycles, that is to say the new moons recur on the same day of the month and the same day of the week. The correspondence, of course, is not quite exact, since the Metonic Cycle is approximate only.

Yet another cycle, called the Cycle of Indictions, found its way into ecclesiastical chronology about the time of the Council of Nicaea. It is a purely artificial period of 15 years and is believed to have had a legal origin, but nothing is known for certain. The product of the three cycles 19, 28 and 15, or 7980 solar years, constitutes what is called the Julian Cycle.[1] It was proposed as a basis of universal chronology by Joseph Justus Scaliger, a man of extraordinary learning [2] who flourished in the sixteenth and seventeenth centuries. This system has been adopted generally, the starting point or *epoch* being taken as January 1, 4713 B.C. This peculiar time was chosen as being the earliest historic date according to

[1] Not to be confounded with the Julian *Calendar* explained above.

[2] He is said to have been the greatest scholar of modern times and to have founded the science of philology. He was not a German, as the Latinized form of his name given in the text might suggest, but an Italian, though a native of Agen near Bordeaux. His scarcely less famous and learned father, Julius Caesar Scaliger, was born in Verona in 1484, and he claimed membership of the princely family of Della Scala. But this descent is not generally admitted, for both father and son, though men of immense attainments, were not entirely reliable in personal matters and altogether they seem to have been unpleasant people to deal with.

Ptolemy's chronology. It is supposed to coincide with the settlement of civilization in Babylonia. It was expected that the selection of this early date as the epoch of chronology would avoid negative dates such as dates B.C., but modern research would seem to indicate that the date was not early enough to justify this expectation. The system has the advantage of being intelligible to everyone and free from the confusing excentricities which are often found in the common systems. For instance, in the system which we use there is no such year as A.D. 0. The first year of our era was A.D. 1, and the year before that was B.C. 1. The Julian Cycle avoids all such anomalies. The system is much used by astronomers who, however, often reckon in days. According to this reckoning A.D. 1 was Julian year 4714. The present year, 1923, is Julian year 6637, and the present day of writing, June 18, 1923, is Julian day 2,423,590.

In concluding this book we recommend the following articles and books to those who desire to pursue the subject:

(1) Articles "Clocks" and "Chronology" in the *Encyclopedia Britannica*.

(2) *The Book of Sun-dials*, by Mrs. Alfred Gatty (London, G. Bell and Sons).

(3) *Old Clocks and Watches and their Makers*, by F. J. Britten (London, E. and F. N. Spon).

(4) *The Marine Chronometer*, by R. T. Gould (London, J. D. Potter).

(5) *The Royal Observatory, Greenwich: its History*

and Work, by E. W. Maunder (London, R. T. S.). It is a real loss to popular scientific literature that this book is now out of print.

(6) *Electrical Horology*, by H. R. Langman and A. Ball (Crosby Lockwood and Son, London). This book suffers from over-condensation, but it is the only one on this part of the subject of clocks.

There are, of course, several highly technical books of great merit on the subject, but a list of these would hardly be of much value to the general reader. The *Watch and Clock-makers' Handbook*, by F. J. Britten is a very useful book. It is written in dictionary form.

Any one interested in clocks and watches should on no account miss seeing the exhibits in the Science Museum, South Kensington, and in the British Museum.

APPENDIX

DIRECTIONS FOR MAKING THE ARMILLARY SPHERE

While it is not desired to discourage accuracy of workmanship, it is desirable to point out that no great amount of it is required for the efficiency of this model. Too much insistence upon accuracy might indeed defeat the object for which the model was designed, which is to show the reader how he may obtain for a few pence a rough model, as good or better for his purpose than one costing pounds. The object of the model is not to provide an exercise in workshop practice, nor to make accurate observations or measurements with it, but to help the imagination.

The polar " axis " is a piece of ½″ dowel rod. The polar disks are of wood 2½″ in diameter, with central holes such that the axis can pass freely through them, but without excessive shake. Each wooden disk should be strengthened by stout tin plates secured on each side of it by four small brass bolts which pass through it. Twelve equidistant radial holes to receive the wire ribs are bored into the edge of each disk to a depth of half an inch with an awl

of rather smaller gauge than the wire. Alternatively, the strengthening plates may be dispensed with, in which case the disks should be of oak or beech or some other hard wood, not less than $\frac{1}{2}''$ thick, and particular care should be taken not to split them when boring the radial holes. For a cage $12''$ in diameter, the wire ribs should be $17\frac{1}{4}''$ long cut from No. 14 Imperial wire gauge brass wire, which is sold in coils of about the right size and therefore ready bent. Ten or twelve coils should be bought to provide a little extra in case of accidents. The ends of these ribs are inserted into the holes in the polar disks to a depth of half an inch. The "equator" is a piece of the same wire $37\frac{1}{2}''$ long, bent into a circle and having its ends united by soldering them into a piece of brass tube $\frac{1}{2}''$ long and of about the same bore as the wire. To make this joint, clean the ends of the wire with fine sandpaper. Insert one of them a quarter of an inch into the brass tube and pinch the tube tightly with pliers on the wire so that it will not move, taking care to pinch only the end of the tube occupied by the wire. Then immerse the tube first into soldering fluid, which can be bought under that name, and then into melted solder. For this purpose only a small quantity of solder need be melted over a gas flame—*e.g.* a cooking stove—in the lid of, say, a cigarette tin. Treat the free end of the wire in the same way, and insert it into the tube. It will not go in very far, since the tube is full of solder, but it can easily be pushed home against the other end of the wire on holding the tube in a gas flame.

Hold the parts in position until the solder sets, which will happen in a few seconds, and the joint is complete. The operation takes little more time to perform than to explain. Twelve shallow equidistant nicks should be made with a file on the outside of the equator wire, and the ribs are similarly nicked at their middle points inside. The equator wire is placed inside the cage so that the proper nicks correspond, and three or four of the joints are temporarily bound with thin string to keep the cage in shape preparatory to soldering. The twelve joints are then soldered, care being taken in soldering that the ribs cross the equator at right angles. This again is done very quickly. To support the cage while soldering, take a piece of $\frac{1}{2}''$ dowel rod and make two shallow saw cuts in its end at right angles to one another to receive the wires, and make a fairly tight fit with them. One cut should be about the diameter of the wire in depth and the other about twice as deep. Then cut away the corners at the intersection of the cuts, so as to leave a small cavity. Clamp or screw the rod in a vertical position, cut end uppermost, and pass the cage over it, resting the joint to be soldered on the top, so that the equator fits in the deeper slot and the rib in the other. Fig. 28 is a plan looking down on the top of the rod, which is represented by the circle. Apply a few drops of soldering fluid to the proposed joint and place a small quantity of solder adjacent to it in one of the divisions of the cavity. Then melt the solder by the application of a hot poker or a soldering iron. The solder will run into the joint

and fill the cavity. If necessary, press the rib down on the equator until the solder sets. A joint thus made has considerable strength, on account of the bead of the solder formed by the cavity. The "ecliptic" is made and applied to the *outside* of the cage in a similar way to the equator, except that nicks should be made on its *inside*, two at the solstitial and two at the equinoctial points. The latter points should be chosen on the equator where a pair of opposite ribs intersect it. Nicks should be made in

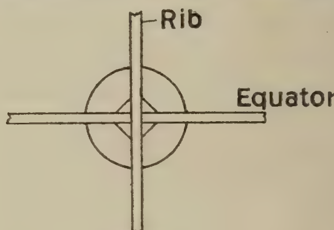


Fig. 28.

the ribs at right angles to them. If these latter pair of nicks are made, one on each side of the equator and at a distance of $2\frac{1}{2}''$ from the equator, the ecliptic will then fit on at its proper inclination of about $23\frac{1}{2}°$ to the equator. The two joints at the solstitial points should be soldered first, these being the only rectangular ones on the ecliptic. After soldering at these four points, taking care that the solstitial ribs cut the ecliptic at right angles, the remaining ribs can then be soldered to the ecliptic. The cage is held in its place on the polar axis by two wire pins or nails driven through the axis at such a distance apart as to bear against the polar disks, but not to distort the cage substantially.

The "horizon" shown in the figures illustrating the text is made of two pieces of thin wood spaced apart to accommodate the polar axis and attached together by wooden cross-pieces screwed to it. The whole forms a circular disk when the two parts are secured together. The wooden cross-pieces are screwed to opposite faces of the horizon disk, and one of them is hollowed out so that the polar axis can lie in the slot when the disk is folded up against it. The disk need not fold up against the polar axis in more than one way. It is pivoted at its middle point to the polar axis exactly half-way between the poles, and the pivot pin should be at right angles to the slot. This pin is a piece of wire driven through the polar axis and clamped down on to the disk by wooden blocks screwed to it. The two halves of the disk must, of course, be inserted separately into the cage when the latter has been mounted on its polar axis, and the parts then screwed together.

The meridian wire passes through holes in the wooden blocks at the opposite ends of the slot, about a quarter of an inch in from the edge of the disk, or $5\frac{1}{2}''$ from the pivot. It also passes through holes in the polar axis $5\frac{1}{2}''$ from the pivot. It consists of a circular wire $35''$ long or a little more. It should be put in position after the whole apparatus has been otherwise assembled, and its ends should be pointed and jammed side by side into one of the holes in the polar axis. It should be a tight fit in the polar axis, the tighter the better, but a fairly loose fit in the horizon, so that the latter can slide upon it but still be held in any desired position by friction.

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